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The Energy Value of the Minimum Visible Chromatic and Achromatic For Different Wave-Lengths of the Spectrum

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PREFACE

In the work reported in this dissertation three important determinations have been made at seven points in the spectrum: the minimum visible achromatic and chromatic and the photochromatic interval. For the first time these determinations have been made by direct measurement in absolute energy terms. The investigation is one of a series of studies the object of which has been primarily to lay a foundation for the exact measurement of human responses in terms that are quantitative or numerically comparable. Such work has been possible only within the last few years. The importance of the study as a foundation for the more scientific phases of medical work on the eye should also be noted. Further work on this and other applications of functional testing to the study and diagnosis of diseases of the eye will be carried on by the author in a research position in the Graduate Medical School of the University of Pennsylvania.

The subject of this dissertation was suggested by Professor C. E. Ferree and Dr. G. Rand of the Department of Psychology of Bryn Mawr College and the dissertation was prepared under their direction. The writer wishes to acknowledge her deep indebtedness to Professor Ferree and Dr. Rand for their careful supervision and constant help during the work on the dissertation and for their great kindness and support during the whole of her graduate course. She takes pleasure also in expressing her appreciation to Dr. Rand for her kindness in making the energy measurements given in Table V. Thanks are likewise due to Dr. Luther C. Peter, Associate Professor of Ophthalmology, Philadelphia Polyclinic and College for Graduates in Medicine, University of Pennsylvania, for his courtesy in sending patients for the section on pathological cases.

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I

INTRODUCTION

By the minimum visible is meant the least amount of light radiation to which the eye is capable of giving a visual response. Obviously the term may be used, broadly, to mean the least amount of light of any composition whatever to which the eye gives a just noticeable response; or, narrowly, as the least amount of the wave-length to which the eye is the most sensitive. Apparently the purpose of a recent group of writers has been to favor the narrower usage of the term although it has been variously applied by different members of the group to determinations made with the light of the stars, the light of a tungsten lamp, and to wave-lengths in the mid-region of the spectrum. The broader usage, which is the older, is more compatible with the purpose of this investigation and will be conformed to in the statement and discussion of results. Used in this sense, the minimum visible is synonymous with the absolute threshold or limen.

Numerous points of interest may attach to the determination of the minimum visible.

(1) There may be a scientific curiosity to know the least amount of energy to which the eye is capable of giving a response and to compare this with the least amount to which the ear or some other sense organ gives a noticeable reaction. Wien, for example, was led to attempt a determination of the minimum visible by his previous work on the minimum audible. A natural extension of this interest is a comparison of the sensitivity of the eye with that of the physical instruments which respond to light. Coblentz has found, for example, that it has, roughly speaking, 300,000 times as great a sensitivity to light radiations as the most improved type of thermopile.

(2) In the evolution of the sense organs, many complex characteristics and adaptations have developed presumably in the interests of functional efficiency. The eye, for example, has

developed to a high degree a selectiveness of response to light radiations. Obviously in adapting light to the service of the eye in problems of illumination and in making a correct use of the eye in the many scientific and technical ways in which it is employed, it is highly important, therefore, to know minutely this selectiveness of response both as to kind and amount. It is also interesting from explanatory and technical points of view to be able to compare the sensory with other known and better understood types of response such as the photoelectric, the photochemical, and the thermoelectric reactions, the action of light on selenium, etc. For example, explanatory theories of the eye's response have already been developed in terms of two of these types of reaction—the photochemical and photoelectric—and all of them, including the sensory reaction, have been utilized at various times for rating light intensities for scientific and technical purposes.

(3) It is generally recognized that the most sensitive means of detecting the eye's abnormality due to natural causes or its subnormality due to pathological conditions and processes is in terms of its lack or loss of sensitivity or power to give response, relative and absolute. There are many practical applications of this principle. For example, (a) one of the ways in which ocular fitness for vocational purposes is rated is a determination of the light and color sense. Eyes vary a great deal in light sensitivity, particularly in their range of sensitivity to light intensities. Many, for example, who are able to qualify for work at medium and high intensities of illumination are disqualified for vocations requiring keen power and quickness of vision at low illuminations. Others lack in color sensitivity, varying from a complete absence of power to sense one or more colors to slight deficiencies which disqualify only for work which requires special powers such as great keenness of discrimination, speed of discrimination, etc. And (b) the most pronounced and earliest manifestation of pathological conditions of the sensory mechanism is the loss of light and color sensitivity. This varies from a slight deficiency to a total loss of function, depending upon the severity and stage of advancement of the pathological condition. The application of the testing of light and color sensitivity to

diagnosis, however, is in its infancy, partly because of the lack of instruments and methods which are feasible for office and clinic work and partly because of a lack of knowledge of norms of sensitivity for the healthy eye and of the deviation from these norms which are characteristic of disease and which differentiate one diseased condition from another.

Some of the known effects of pathological conditions are a diminished light sensitivity, a particular and differential manifestation of which is a greatly diminished or entire absence of power to see at low illumination, absolute and partial loss of color sensitivity, changes in the relative sensitivity to the different colors, and changes in the interval between the achromatic and chromatic thresholds of sensitivity to colored lights—the photochromatic interval. As has already been stated, but little use has been made of the testing of light and color sensitivity of the central retina by the medical profession. Their work up to the present time has been confined chiefly to the mapping of the fields of light and color sensitivity. Even this has been almost prohibitive because of the care required to obtain an acceptable precision of result, and the time consumed in making the determinations in a sufficient number of meridians. It is a matter of great interest and importance, therefore, to see how far central sensitivity testing, which with methods amply sensitive for diagnostic work need consume but little time, can be substituted for field taking. As already indicated, field taking is at best a time consuming and difficult performance from the standpoint of the patient, the physician, and the apparatus and controls required.

While the medical aspects of the problem have made the strongest appeal to the writer's personal interests, it has been deemed advisable to subordinate them at this time to an endeavor to build a sounder groundwork on which to rest the applications. It is important in every applied field that there should be standards of reference as to apparatus, methods, and results against which the deviations made in the interests of convenience and feasibility can be checked and evaluated and from which fresh starts can be made.

There are two important aspects of the testing of retinal sensitivity: the testing of the absolute sensitivity to the different wave-lengths of light and a determination of the comparative or relative sensitivity to these wave-lengths. Differences in both of these regards are fundamental in all of the fields in which sensitivity testing and its results may be applied. To serve as a standard of reference it is obvious that absolute sensitivity should be expressed in absolute terms both with regard to the composition of the stimulus and to its intensity, *i.e.,* for the eye, in terms of wave-length and energy value of light. It is equally obvious that if the sensitivities to the different wave-lengths are to be compared, the intensity values of the stimulus of which sensitivity is taken as the reciprocal must be expressed in terms that are numerically comparable, *i.e.,* in terms of the physical intensity or energy value of the lights employed. Norms either of chromatic or achromatic sensitivity have not as yet been determined in absolute terms. Fragmentary attempts have been made on the basis of results obtained from a few observers to express achromatic sensitivity in relative terms. The investigation of chromatic sensitivity, however, has not progressed even this far. The work of establishing norms of absolute and relative sensitivity for both of these types of response will involve expenditure of a great deal of time and effort and the coöperation of many people. Even to contemplate it seems overambitious at this time. However, every work must start from small beginnings. It has been the purpose of this study to make such a beginning of the study of the thresholds of chromatic and achromatic sensitivity.

The following determinations have been made at seven representative points in the spectrum:

(1) The achromatic threshold.
(2) The chromatic threshold.
(3) The photochromatic interval.

Twenty-one observers have been used in making these determinations and in every case a direct energy measurement was made of the light used to stimulate the eye. In addition, determinations were made in a limited number of pathological cases.

II

HISTORICAL SUMMARY

As early as 1888 Hermann Ebert (1) attempted to ascertain numerically the relative achromatic sensitivity of the eye to wavelength. Two lines of evidence had led him to suppose that the eye might have a maximum of sensitivity to green. In his conclusions the emphasis is on the position of this maximum rather than on the details of the threshold visibility curve. The first problem, his more immediate incentive, was the explanation of the striking simplicity of the spectra of the gaseous nebulae which in most cases consist merely of lines in the green and the blue-green, λ 500,495 and 480 $\mu\mu$. Two theories of this phenomenon had already been advanced: first, that only these wave-lengths are emitted, and second, that there is selective absorption in intranebular space. Ebert thought it more probable that the cause lies within the observer. That is, if the eye should prove to be most sensitive to green, it would be reasonable to expect that in a weak spectrum, such as that given by the gases, only the green would be visible. His second, more general motive, was the reopening for discussion of the whole psychophysical question, a subject made pertinent by the work of Weber (2) and Stenger (3) on Draper's law during the previous year. In discussing the results obtained in this work, Weber had assumed a direct proportionality between the responses of the eye and the energy of the light wave. Stenger had pointed out the incorrectness of this assumption but his discussion of the matter had been slight enough to warrant a more complete investigation by Ebert.

Draper's law refers to the order in which the wave-lengths of the visible spectrum emitted by incandescent solids reach the threshold of sensation with increase of temperature. Draper had stated that all metals begin to glow at the same temperature, about 525° C., and that the development of the light emission runs the following definite course: at 525° the light emitted gives a spectrum which reaches from line B to line b; at 625° from B to F; at 718° from B to G; and at 1165° it gives a spectrum approximating that of the sun in extent. According to Draper, then, the spectrum of a glowing solid whose temperature is gradually increased develops practically in one direction only—from red to blue.

In the course of some experiments on the relation between the brightness and consumption of energy in carbon lamps, Weber had noted some entirely unexpected phenomena which caused him to doubt the correctness of this law. Watching the development of the light emission of the carbon filament with increase of temperature in a dark room, he noted that the red glow was not the first light visible, but that another light appeared and underwent an entire series of changes before there was any sign of color. This light he designated as "gespenstergraue" or "düsternebelgraue." At first it was very unstable, although whether its rapid appearances and disappearances were due to change of intensity of the light because of fluctuation in the temperature of the filament, or whether they are due to an eye phenomenon, he did not know. With a slight increase of intensity the light became a little less variable although it retained its "düstergraue" quality. With greater increase the gray lightened, and the coloration gradually changed through an ashgray to a definite "gelblichgraue." By the time the red glow was visible, the light had become fixed, losing the flickering quality which it had had throughout the previous changes.

A prismatic analysis of this first gray light with the complete spectroscope was not possible because of the weak intensity, but Weber was able to observe the changes through a direct vision prism, and, at slightly higher intensities, through a grating. The spectrum of the "düsternebelgraue" light, when first strong enough to be seen through the prism, consisted of a homogeneous gray strip which occupied the position where at higher intensities yellow and yellow-green appeared. As the temperature was increased this strip broadened and brightened. When the temperature had reached a degree such that with the naked eye the light looked "gelblichgraue," its spectrum was seen as a broad band, yellowish-gray in the center and shading to a weak gray on either side. When, viewed by the naked eye, the light was reddish, there appeared in the spectrum at one side of the gray strip a small " feueroth " space, and almost simultaneously on the other side a gray-green strip. As the light became whiter with increase of temperature the spectrum continued to develop until finally the entire spectrum was present. This description of the light emission of a glowing solid was verified by Stenger, who repeated Weber's experiment.

It is in his conclusion that Weber makes the assumption that visibility is proportional to energy, an error which, as was stated above, was pointed out by Stenger. Weber states his conclusions as follows:

> " Das Spectrum des glühenden Kohlenfadens wächst also bei steigender Temperatur nicht einseitig, in der Richtung vom Roth nach dem Violett, sondern entwickelt sich, von einem schmalen Streifen ausgehend, genau von seiner Mitte aus, gleichmässig nach beiden Seiten. Die dem Auge zuerst erscheinende, den Ausgangspunkt der Spectrumsentwickelung bildende Strahlung ist dieselbe Strahlung, die im vollständig entwickelten sichtbaren Spectrum dem Auge mit der grössten Helligkeit leuchtet und in dem schwarzen Flächen der Thermosäule und des Bolometers die maximale Energie entwickelt.
>
> " Daraus ist wohl der Schluss zu ziehen, dass diese Strahlung mittlerer Wellenlänge deswegen dem Auge am frühesten sichtbar wird. weil sie auch schon bei der Temperatur der beginnenden Grauglüht die maximale Energie besitzt, infolge dessen ihre lebendige Kraft am frühesten jenen Schwellenwerth übersteigt, welcher vorhanden sein muss, um eine Lichtempfindung zu veranlassen, und dass die übrigen Strahlungen kleinerer und grösserer Wellenlänge dann bei steigender Temperatur der Reihe nach dem Auge sichtbar werden, sobald deren lebendige Kraft einen Schwellenwerth ähnlicher Grösse überstiegen hat."

Stenger, referring to Langley's (4) results on the energy distribution of the sun's spectrum, showed that since the greatest energy is in the red, not in the green or yellow-green, the eye must be *selectively* sensitive, and that the maximum of this sensitivity must lie in the green.

It was at this point that Ebert took up the problem. The details of his experiment are as follows: The source of light was a gas flame which illuminated from behind a screen of oiled paper. This screen was assumed to be evenly illuminated and was focussed on the slit of the spectroscope by a lens 12 cm. in diameter placed at 125 cm. from the slit. The observer, looking through the objective slit, saw the face of the prism filled with spectral light. The intensity of the light was then reduced until it was no longer visible. For each wave-length used, determinations of the threshold were made in ascending and descending series, and the mean of the two series calculated. The variation amounted to between 2 and 3 per cent. His values are for only five different wave-lengths and for two observers. The length of the adaptation period is not given; Ebert states merely that the experiment was performed after " sufficient " dark-adaptation.

The reduction of the light intensity was obtained by a diaphragm, .07 cm. in diameter, placed between the focussing lens and the collimator slit, and so mounted that it could be moved over the entire distance—125 cm. As this diaphragm is moved nearer to the focussing lens, it decreases the diameter of the used portion of the lens, thus reducing the intensity of light focussed at the slit. If E is the distance of the diaphragm in cm. from the slit, and D the diameter of the used portion of the lens, then

$$D = \frac{125 \times .07}{E}$$

The intensity of any part of the spectrum is then proportional to D^2.

The distribution of energy in the spectrum of the light source used was calculated indirectly by combining the results of Langley mentioned above, with those of Meyer (5), who had checked the energy distribution of a gas flame, the source used by Ebert, against that of the sun. Langley, using a bolometer, had determined the energy distribution of the sun's spectrum in relative terms, *i.e.*, in terms of galvanometer readings—no absolute values are given. Meyer had compared photometrically the spectrum of a gas flame with that of the sun, obtaining a series of ratios representing the energy distribution of the gas flame relative to that of the sun. Ebert, to get the energy distribution of his own source, multiplied the values given by Langley by the appropriate ratios as given by Meyer. The results of these calculations are shown in Table I, quoted from Ebert.

TABLE I

Farbe	Mittlere Wellenlänge	Helligkeit Gaslicht Helligkeit Sonne (Meyer)	E Sonne (Langley)	E Gaslicht
Roth	675 μμ	4,07	62	252
Gelb	590 μμ	1,00	45	45
Grün	530 μμ	0,43	28	12
Grünblau	500 μμ	0,43	22	10
Blau	470 μμ	0,23	14	3

In this table the second column gives the middle wave-length of the various spectrum bands used; the third volumn gives the ratio of brightness of gas flame divided by brightness of sun for the particular wave-length; the fourth column gives the relative energy of the same wave-lengths as determined by Langley; and the fifth, the product of the third and fourth, shows the *relative* energy distribution in the spectrum of a gas flame.

Such a calculation would, at best, yield results only approximately correct, and in this case it is still further open to criticism in that Ebert did not use exactly the same wave-lengths as Meyer. As was said previously, however, he lays little stress on the shape of the visibility curve, insisting only that the maximum lies in the green.

The final threshold values were obtained in relative terms by multiplying the values given in column 5 of the above table by D^2. Since sensitivity is taken as the reciprocal of the threshold value of the stimulus, the relative sensitivities of his observers were as the reciprocals of these products. The values of these reciprocals are given in Table II.

TABLE II

Observer	Red	Yellow	Green	Blue-Green	Blue
S.	1/25	1/15	1	1/1.3	1/3
E.	1/34	1/17	1	1/2	1/4

In 1889 Langley (6) himself published results bearing on the visibility of radiation. He wished " to make the novel calculation as to the actual amount of energy either in horse-power or any other unit, required to make us *see*."

Unlike Ebert, Langley determined the minimum visible by means of reflected light. A piece of white paper on a black screen was illuminated by spectral light of different wave-lengths. As source he used the sun—reflecting its rays into the spectroscope by means of a siderostat mirror. The gross reduction of intensity was accomplished by reducing the effective area of the collimating lens by placing before it a metal plate pierced by a minute aperture, by a sectored disc, and by a glass screen very lightly smoked. The finer reductions were made by varying the width of the collimator slit. By actinometric measurements, Langley found the solar radiation to be 1.5 calories per square centimeter per minute. Knowing the reductions made, and estimating the absorption through the optical system, he calculated the values of the minimum visible for four wave-lengths to be as shown in Table III.

TABLE III

Color	Wave-length	Energy (ergs)	Ratio of Energies
Crimson	750 $\mu\mu$	1/780	450000
Scarlet	650 $\mu\mu$	1/1600000	230
Green	550 $\mu\mu$	1/360000000	1
Violet	400 $\mu\mu$	1/1500000	240

These results are for one observer only. The fourth column shows the relative energy values of the threshold for the four wave-lengths in question. Langley says of these results that they are subject to variations of a wide range, and may perhaps be in error by as much as 100 per cent.

The next results bearing on the subject are those of König (7), who, as part of an extended experiment on the relative brightness of different bands in the spectrum at various intensities, determined a threshold visibility curve. He used the Helmholtz spectrum color mixer, reducing the intensity of the light by means of slit width. Like Ebert, he used Langley's figures representing the relative energy distribution in the sun's spectrum, multiplying them by ratios previously determined by himself and Dieterici in a comparison of the energy distribution of the spectrum of a triplex gas burner (the source used) with that of the sun. His data are for two observers and fourteen wave-lengths. Table IV shows the relative sensitivity of the two observers to the wave-lengths employed. The method of calculation is similar to that of Ebert, described above.

TABLE IV

Wave-length	Observer			Wave-length	Observer		
	A.K.	R.R.	Av.		A.K.	R.R.	Av.
670 μμ	.00019	.00017	.00018	535 μμ	.75	.60	.68
650 μμ	.00047	.00056	.00051	520 μμ	.98	.83	.90
625 μμ	.0038	.0048	.0043	505 μμ	1.00	1.00	1.00
605 μμ	.015	.019	.017	490 μμ	.86	.75	.80
590 μμ	.045	.033	.039	470 μμ	.50	.50	.50
575 μμ	.12	.12	.12	450 μμ	.23	.26	.25
555 μμ	.36	.33	.35	430 μμ	.047	.059	.053

Pflüger (8), in taking up the problem in 1902, adopted a procedure similar in principle to that of Ebert. Unlike Ebert, however, he determined the energy distribution of the source directly with a thermopile, although only in relative terms. Also a greater number of observers was used.

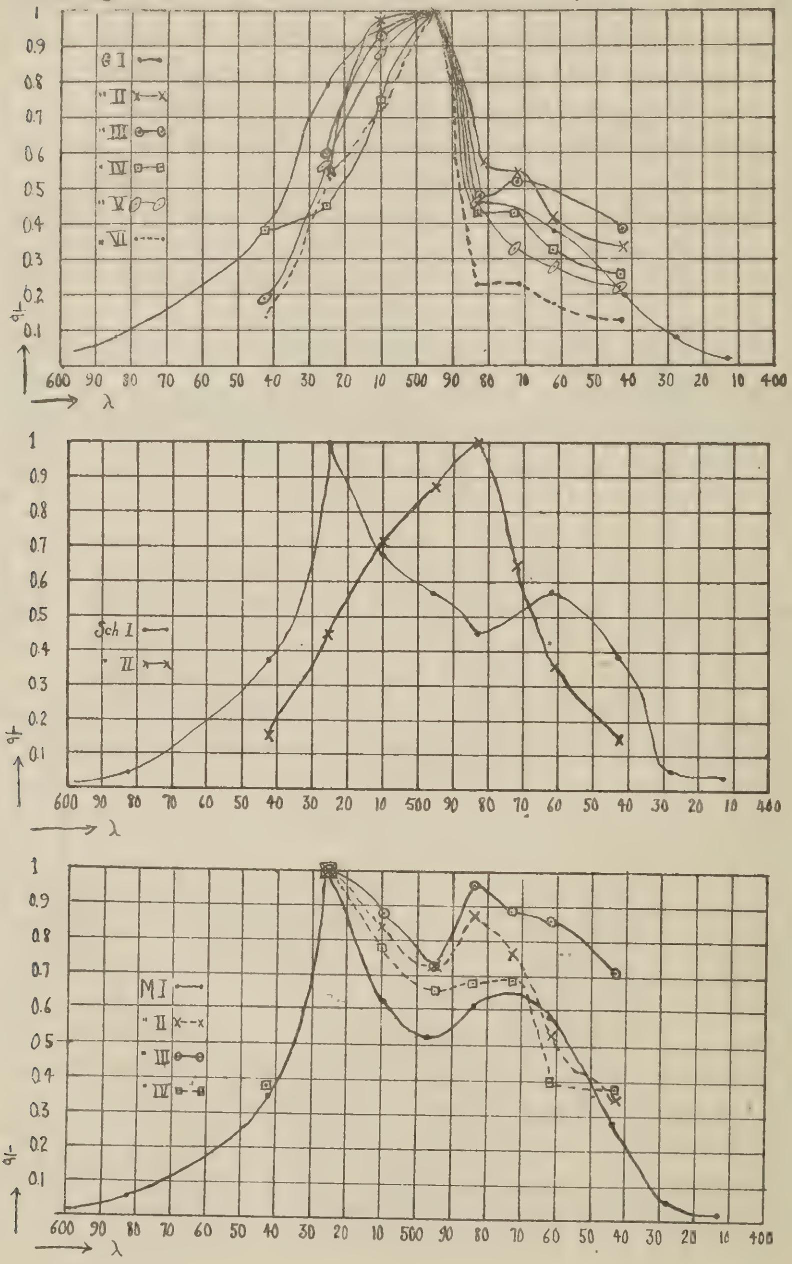
A Nernst filament was used as source, the light from which was focussed on the slit of the spectrometer by a condensing system composed of two triple achomatic lenses. This seemed to satisfy best the need for a source whose intensity was both constant and sufficiently great to permit of direct measurement in the violet. The energy measurements were made by means of a Rubens thermopile mounted at the objective of the spectroscope, and a DuBois-Rubens galvanometer. The radiometric apparatus was not, however, calibrated against a standard, and the energy curve is, therefore, in terms of galvanometer readings, not absolute units.

In order to allow for the reduction of the light to the threshold of sensation, slight changes in the arrangement of the apparatus had to be made. The ocular slit was shortened to ¾ mm. in height, which with the breadth of ½ mm. was considerably smaller than the observing pupil. Milk glass was placed over the collimating slit to give evenness of field brightness, and the focussing lenses removed. The energy measurements were corrected for the absorption of the milk glass and an attempt was made to compensate for the absorption of the lenses by inserting glass plates in the beam of light. A bar four meters long was added to the collimator arm. The illumination of the milk glass could then be varied by changing the position of the Nernst filament on this bar. A further reduction was made by introducing a sectored disc into the path of the ray, and the final reduction was obtained by varying the slit width. The observer, looking through the objective slit, saw the face of the prism illuminated with spectral light. To aid in maintaining fixation a milled ring was placed at the ocular slit. The diameter of the lighted surface subtended an angle of about 12 degrees, its image being, therefore, much larger than the fovea, larger even than the macula.

The procedure was very tedious, says Pflüger. Three readings were taken for each determination; then the whole series was repeated in reverse order. With few exceptions the second series was found to correspond to the first within the experimental error of the first. When this was not the case the whole series was repeated. Errors for single measurements were high, sometimes reaching 10 per cent. The average error was 4 per cent. Results are given for nine observers, and the curves for different days are plotted separately. The original intention was to average all the results for a given observer, but so much diurnal variation was found to exist that the plan had to be abandoned. The question of this large variation from day to day being found simultaneously with a comparatively small variation for any one sitting will be discussed later. In a few cases nineteen points in the spectrum were employed as stimuli, but the bulk of the curves are plotted for eight points. To get the final values the slit width readings were averaged, then reduced to what they would have been with the source at a distance of one meter and with 360° open sector. The reciprocal of this value is taken as the measure of the sensitivity. The greatest sensitivity in any series is taken as unity, and the other values are made proportional. The position of this maximum sensitivity varies widely, not only from individual to individual, but from day to day in the results of the same individual. Three curves selected as typical are reproduced in Figures I, II, and III. Figure I gives the curves for an observer who shows comparatively little diurnal variation. For six days the maximum sensitivity was at 495 $\mu\mu$. There is considerable variation, however, at other wave-lengths. Figure II gives curves for an observer whose diurnal variation is extreme. For example, on two days the maximum sensitivity occurred respectively at 525 $\mu\mu$ and 485 $\mu\mu$. Figure III gives the curves of an observer in which the tendency toward a secondary maximum is pronounced. Varying degrees of this tendency are shown in many other curves in Pflüger's series. From such data it is evident that Pflüger could draw no conclusions as to the exact shape of the threshold visibility curve—he could merely give the general characteristics of such a curve. His conclusion is:

> "Die absolute und die relative Farbenempfindlichkeit des Auges, gemessen bei den Schwellenwerten der Reizempfindung, ist grossen individuellen Verschiedenheiten, und, bei demselben Auge, grossem Wechsel unterworfen. Die Empfindlichkeit ist am grössten für den Spectralbereich $\lambda = 495\ \mu\mu$ bis $\lambda = 525\ \mu\mu$. Sie kann für $\lambda = 717\ \mu\mu$, den 33000ten, für $\lambda = 413\ \mu\mu$ den 60ten Teil des Wertes im Grün betragen."

FIGURES I–III. Sensitivity Curves (Pflüger).
Showing the diurnal variation in achromatic sensitivity of three observers.



III

APPARATUS AND PROCEDURE

In any quantitative determination of the amount of light needed to arouse a just noticeable sensation for any given group of wave-lengths there are two essential requirements: (1) We must have a means of presenting to the eye the desired range of wave-lengths free as nearly as possible from alien wave-lengths; and (2) we must have some means of measuring the energy of the stimulus thus presented and of reducing its intensity by known amounts. The greater part of the spectroscopic and radiometric apparatus needed to fulfil these two requirements was already in use in the Bryn Mawr laboratory when the present work was undertaken.[2] The description of the apparatus as modified to meet the needs of the present investigation, together with the necessary additions, is given under five headings: the source of light; the spectroscope; the apparatus for presenting the light to the eye; the devices for reducing the intensity of light; and the radiometric apparatus. The procedure is described under two headings: the energy measurements; and the methods of observation. A drawing showing the path of the beam of light and the arrangement of the apparatus is given in Figure IV; a photograph of the assembled apparatus in Figure V.

A. The Source of Light. The source of light was a Nernst filament operated at 0.6 ampere. This source was chosen because when properly seasoned it gives a light very constant in both intensity and radiometric composition, and at the same time sufficiently intense to permit of direct energy measurement. Its shape also well adapts it for use with the slit of the spectroscope, *i.e.,* the shape is such as to make it possible to utilize for the illumination of the face of the prism a relatively large part of the light emitted. When in use the filament is placed directly in front of the slit and as close to it as is possible. This placement

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[2] For description of this apparatus see References (9) and (10).

of the filament, however, presents two difficulties. In the first place the Nernst material must be heated before it will conduct the electric current. This requires that the filament be moved from its position in front of the slit prior to each period of work. In the second place the terminal wires, which are of platinum and very pliable, give little stability of position to the filament. Because of these difficulties a special mounting had to be devised which would provide for the adjustments required for the removal and precise resetting of the filament and would give the rigidity of support needed to prevent sagging or other displacement of the filament from its position in front of the slit. On this latter point it may be noted that if care is not taken that the light which enters the slit come always from the same part of the filament, variations both in its composition and intensity may occur. This mounting is shown in Figure IV.

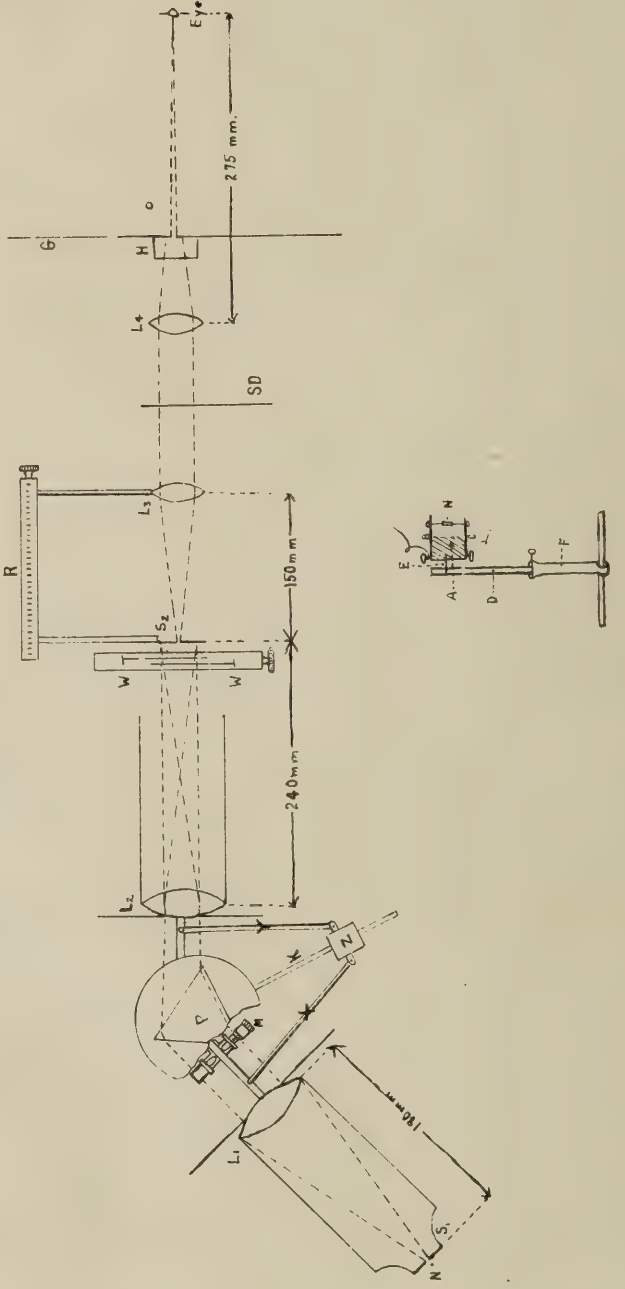
B and C are two metal arms at the ends of which are attached the terminal wires of the filament N. B and C are supported by a piece of asbestos A, which is in turn fastened to the rod D by a pin E. E serves a double purpose: by its use B and C are supported in a manner which not only provides for both heat and electric insulation, but which also allows a slight rotary movement necessary for perfect alignment of the filament with the slit. The height of D is adjustable and F is fastened by a collar to a round rod attached to the collimator arm, thus permitting movements of the mounting back and forth, right and left, and up and down. Around the whole is a metal housing ventilated at top and sides, but in such a manner as to remain light-proof. The filament is connected in series with a Weston ammeter graduated to 0.02 ampere; a ballast which both reduces the current and compensates for the change in the resistance of the Nernst with change in temperature; and two adjustable rheostats, one coarse, the other fine. The former is used to cut down the current to approximately the desired value and the latter to correct for the fluctuations in the line.

B. The Spectroscope. A diagramatic representation of the spectroscope is shown in the drawing given in Figure IV. S_1 is the collimator slit; L_1, the collimator lens; P, the prism; L_2, the objective lens; S_2, the objective slit. L_3 to L_4 is the system for focussing the light on the eye. The collimator slit S_1 is 12 mm. high, and its width can be varied by means of a micrometer screw fitted with a head graduated to read to thousandths of an inch. This slit was set at a width sufficient to allow of the radiometric measurements being made with precision, and was kept constant throughout the experiment. Lenses L_1 and L_2 are both Zeiss triple achromats, 60 mm. in diameter; the collimator has a focal length of 180 mm., the objective of 240 mm. A carbon bisulphide prism 105 mm. high, with a refracting angle of 60 degrees, was used. With the exercise of a reasonable amount of precaution to keep the CS_2 free from impurities and to maintain a uniform temperature in the room, this prism has given satisfaction. If the temperature is not kept constant the change of refractive index of the CS_2, resulting from the change in temperature, necessitates frequent checking and resetting of wave-length. The objective slit is 0.342 mm. wide and adjustable in height. For the radiometric measurements a height of 10.4 mm. was used; for the work with the eye this was reduced to 1.85 mm. The greater length was necessary in order to obtain an intensity sufficiently high to make the energy measurement; for the eye work, however, a much smaller slit is needed in order that the image which is focussed on the eye may fall entirely within the pupil. This slit is mounted on an independent base screwed to the table in a fixed relation to the base of the spectroscope. In order that the distance of the slit from the lens L_2 may be adjusted for the different focal distances of different wave-lengths, the frame on which the slit is mounted is furnished with a rack and pinion R. Lens L_3, which serves as collimator in the system for focussing the light on the eye, is mounted on the same rack and pinion so that the distance between S_2 and L_3 (the focal length of L_3) remains always constant.

In order to obtain automatically minimum deviation for all wave-lengths falling on the objective slit, the spectroscope was fitted with a special attachment for the purpose. K in Figure IV is a rod fastened to the prism table in such a position as to be continuous with the radius of the table which bisects the refracting angle of the prism; X and Y are two rods of equal length fastened at one end to the two arms of the spectroscope at points equidistant from the center of the prism table, and at the other to a collar Z, which is free to play back and forth along rod K. M is a micrometer screw with a graduated head which is used to move the collimator arm through the small angles needed to change the wave-length. Opposite this screw is a plunger working against a spring. The collimator arm is held between the screw and the plunger so that it responds to a movement of the screw in either direction. By this attachment the prism is always turned through half the angle traversed by the collimator arm in changing the wave-length. Therefore if the prism is once set for minimum deviation for the D-line, there will also be minimum deviation for any other wave-length. That is, when the prism is set for minimum deviation, the line bisecting the refracting angle of the prism also bisects the angle made by the incident and emergent rays, hence if in changing the wave-length the angle between the incident and emergent rays be changed a given amount by a movement of the collimator arm, the prism must be moved through half that angle in order that the line which bisects its refracting angle will also bisect the angle made by the incident and emergent rays.

In all quantitative work on color sensitivity it is very important that the light employed be as homogeneous as possible as to wave-length. The presence of alien visible wave-lengths affects the determination of chromatic sensitivity in two ways: (1) It decreases the amount of the color response through physiological inhibitions and interactions, and (2) it increases the value of the energy measurements. In the work in this laboratory determinations made with and without provision for absorbing impurities due to scattered light, internal reflections, etc., show differences large enough to be considered significant. In the present investigation the aim has been to obtain a degree of purity such that any portion of the spectrum used should show only one band when examined with a second spectroscope. In order to secure purity of light the following precautions were taken. The spectroscope was provided with the minimum deviation attachment already noted. Great care was employed in eliminating as far as possible all stray light and internal reflections. The source was housed as described above and a screen was placed at the objective lens to prevent any stray light from the prism from reaching the farther parts of the system. As far as could be all surfaces that might either admit or reflect extraneous light into the path of the refracted beam were blackened, and as a final precaution a light-tight housing was built around the whole apparatus from just in front of the collimator slit to just beyond the lens which focussed the light on the eye. This compartment was large enough to permit of the experimenter working inside. Even with these precautions, however, some impurities remained, chiefly those due to reflections from the surfaces of the lenses. These were absorbed out by very thin gelatine filters, carefully selected with reference to the bands to be eliminated. The gelatine filters were held in place over the objective slit by small clips fastened on either side of the plate containing the slit. The filters were used both for the radiometric measurements and for the threshold determinations.

C. Apparatus for Presenting the Light to the Eye. There are several methods by which we may obtain a homogeneously illuminated surface suitable for determining thresholds of sensation: (1) Spectrum light of the desired range of wave-lengths may be allowed to fall on some diffusively reflecting surface, such as magnesium oxide, which in turn is viewed by the eye; (2) spectrum light may be allowed to fall on some diffusely transmitting surface; or (3) spectrum light may be focussed directly on the pupil of the eye by means of a double convex lens. The third of these possibilities was chosen for this work. The use of either of the first two methods necessitates the assumption that the reflecting or transmitting surface is absolutely nonselective to wave-length. Both methods, moreover, are very wasteful of light—not only is there a comparatively high percentage of absorption, but also only a small percentage of the light coming from any point of the stimulus surface enters the pupil of the eye. Under these conditions it would be very difficult to specify accurately in radiometric units either the unit density or the total


Eye
275 mm.
O
G
H
L4
SD
L3
R
150mm
S2
W
W
240mm
L2
Z
Y
X
P
M
L1
180mm
S1
N
N
B
C
L
E
A
D
F

amount of the light at the eye. That is, the energy value at the eye could not be measured; it could be calculated only approximately. An accurate energy specification is possible, however, when the light is focussed on the eye. The light, by this method, does not spread from the stimulus opening as if emanating from a source, but is concentrated into an image on the pupil of the eye—an image of the objective slit of the spectroscope. The amount of energy concentrated into this image can readily be determined with the radiometric apparatus to be described later.

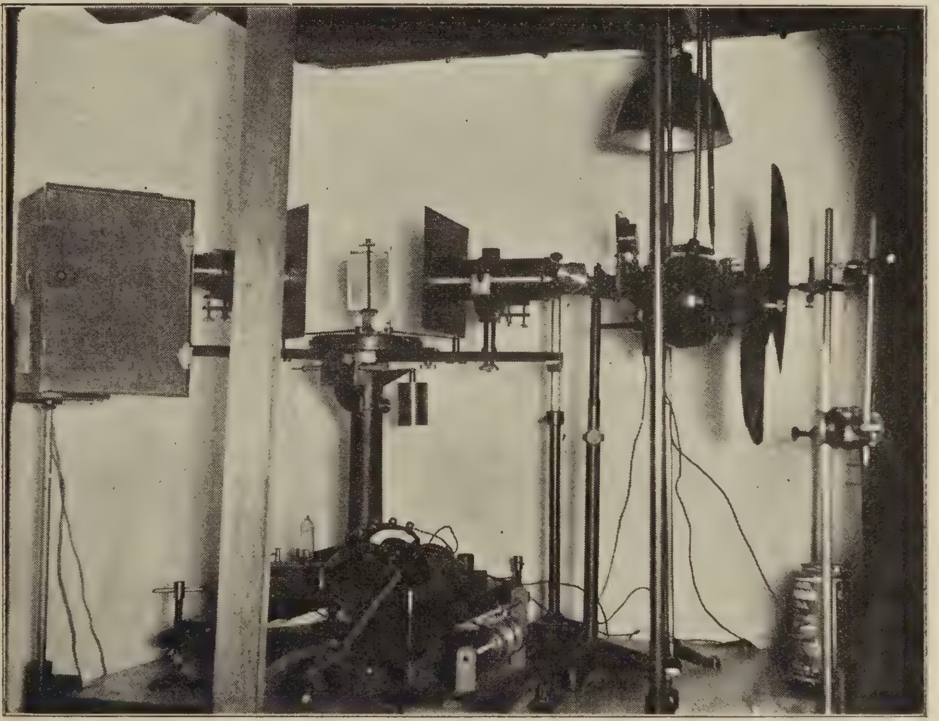


FIGURE V

In order to present the stimulus in compliance with the above plan, the rays of light emerging from the objective slit are first rendered parallel by lens L_3 (Fig. IV) placed at its focal length (150 mm.) from the objective slit, and are then focussed on the eye by lens L_4, focal length 275 mm. In this way ample space is obtained for the introduction into the system of any apparatus necessary for reducing the intensity of the beam of light, *i.e.,* sectored disc, filters, etc. The dimensions of the image at the eye were determined by photographing it on a plate carefully mounted in the plane of the pupil and measuring the photographed image with a micrometer comparator. These dimensions were 3.7326 mm. × 0.6956 mm. Since this is well within the pupil of a dark-adapted eye, the use of an artificial pupil with its attendant difficulties is avoided.

In front of L_4, 240 mm. from the eye, a screen G is placed containing a circular opening O, 10 mm. in diameter, which serves to diaphragm the lens L_4 to the desired stimulus aperture. When the eye is in position the exposed area of the lens L_4 is seen filled with light. The visual angle subtended by this area is $2^\circ\ 2.2'$.

D. Means of Reducing the Intensity of Light. Because of the small amount of energy required to arouse a just noticeable sensation of light, it would be impossible to measure this energy directly with a thermopile. It is necessary, therefore, to measure the energy at a high intensity and to reduce this intensity by known amounts to the intensity required. In order to obtain the range of reduction necessary for all observers, three methods of cut-down were utilized.

1. *The Filters.* The main reduction of light was made by the insertion in the light beam of neutral filters, combinations of which allowed for a possible range of transmission of from 1148×10^{-5} to 141×10^{-12}. The filters are of gray gelatine mounted between glass, 25 mm. by 25 mm. They were made by the Eastman Kodak Company. The densities were specified by the Eastman Kodak Company and the transmission of each filter was calculated by the formula:

$$\text{Density} = \log \frac{1}{\text{Transmission}}$$

A holder designed to take any combination of filters up to eight was placed at H in contact with the screen G. This position of the filters precluded the possibility of any scattered light not completely absorbed being transmitted through the screen opening to the eye of the observer.

2. *The Sectored Discs.* Any further large reduction needed was obtained by the use of a pair of sectored discs inserted at SD. These discs were rotated by a small motor suspended from above by coiled springs to absorb vibration. The range of open sector used was from 180° to 0°.

3. *The Wedges.* The final reduction was made by means of the two wedges WW mounted immediately in front of the objective slit. Early in the work it was realized that for any accurate threshold determinations a means must be had of making very small changes in the intensity of the stimulus, and that the method employed must insure a perfectly uniform reduction throughout the cross section of the beam of light. A single wedge such as is ordinarily employed does not give this required uniformity of reduction. When placed in front of the slit, no matter how fine the gradation in density, there is always a slight difference in transmission between the opposite edges of the used portion of a single wedge. A double wedge device was therefore planned to obviate this difficulty. The two wedges were made according to specification and calibrated by the Eastman Kodak Company. Like the filters, they are of neutral gelatine mounted between glass. The wedges are identical, each being 135 mm. by 13.5 mm., and so constructed as to cover the same range of transmission. They are mounted parallel to each other in holders which are operated by a micrometer screw. These holders are provided with right- and left-handed threads. As the screw is turned the wedges move in opposite directions, each wedge traveling in front of the other through a path equal, if need be, to twice the length of one wedge, that is, from a position of juxtaposition at the thin end of each wedge to a position of juxtaposition at the thick end. Since the density gradients of the two wedges are identical and the wedges move in opposite directions, it is obvious that the resultant densities will be the same from point to point throughout the overlapping section. A consideration of the range of movement shows further that a series of densities may be obtained

varying by minute amounts from the sum of the minimum densities of both wedges, through the sum of the minimum of one and the maximum of the other to the sum of the maxima of both.

The density in this case also equals the log of $\frac{1}{\text{Transmission}}$.

E. The Radiometric Apparatus. The apparatus used consisted of a linear thermopile of silver and bismuth couples, a Paschen small coil galvanometer especially constructed for the thermopile employed, and suitable auxiliary apparatus. These instruments were constructed by W. W. Coblentz of the Radiometric Division of the Bureau of Standards. The apparatus has been described in an article by Dr. Ferree and Dr. Rand (10), and the reader is referred to this article for further details. All the radiometric measurements were made by Dr. Rand, to whom I am deeply indebted for the values given below. The procedure of making these measurements is quoted from the article just mentioned.

F. The Energy Measurements. The apparatus for measuring the energy is so planned that measurements may be made at the objective slit, at the stimulus opening, and at the eye. A description at one of these places, namely, the objective slit, is sufficient to show in a general way the method employed.

" The thermopile to be used was placed in position immediately behind the slit and a blackened aluminum shutter was interposed in the path of the beam of light between the slit and the end of the objective tube of the spectroscope. Preliminary to the exposure of the thermopile to the light to be measured, the current sensitivity of the galvanometer was tested by means of a special device provided for this purpose in the construction of the galvanometer. With regard to this procedure it may be pointed out that the current sensitivity of the galvanometer varies with the period or time of the single swing of its needle system. Since it is not possible to control the field so as to get this period always the same, it is necessary, if results are to be compared, to take some sensitivity as standard and to convert all readings into deflections for the standard sensitivity by means of a correction factor determined at each sitting. (For a detailed description of the method of determining this factor, see PSYCHOL. REV. MONOG., 1917, **24**, No. 2, pp. 60–65.)

"The thermopile was next connected with the galvanometer and the light allowed to fall on its receiving surface until a temperature equilibrium was reached (ca. 3 sec. for our thermopile). The deflections were read by means of the telescope and scale and the readings are corrected to standard sensitivity by means of the factor previously determined. The final step in the process of measuring was the calibration of the apparatus, *i.e.*, the value of 1 mm. of deflection in radiometric units was determined for the area of thermopile exposed. To do this a radiation standard, the value of the radiations from which is already known, had to be employed. The standard used by us was a carbon lamp specially seasoned and prepared for the purpose by W. W. Coblentz. This lamp was placed on a photometer bar 2 meters from the thermopile and operated at one of the intensities for which the calibration was made, in our case 0.40 ampere. The thermopile was exposed to its radiations with the same area of receiving surface as was used in case of the lights measured, and the galvanometer deflection was recorded. From the deflections obtained the value of 1 mm. of deflection, or the radiation sensitivity of the apparatus under the conditions given, was computed from the known amount falling on the surface of the thermopile. Having the factor expressing the radiation sensitivity of the apparatus, the deflections produced by the wave-lengths of light measured were readily converted into energy units."

The radiation sensitivity of the linear thermopile as used in the present investigation was computed from the following data. The energy value of the radiations per square millimeter of receiving surface from the standard lamp at a distance of 2 m. operated at 0.40 ampere was 90.70×10^{-8} watt. The deflections of the galvanometer produced by this intensity of radiation falling on the same area of receiving surface as was used in measuring the lights employed as stimuli, when corrected (a) to a sensitivity of i = 1×10^{-10} ampere, and (b) for the absorption of the glass cover of the thermopile, was 323.85 mm. The area of the surface exposed was 3.5657 sq. mm. The value of 1 mm. of galvanometer deflection, or the sensitivity of the instrument for the area of receiving surface used, was, therefore, 998×10^{-11} watt. By means of this factor the galvanometer readings produced by the different wave-lengths of light were readily converted into the energy value of light falling on the receiving surface of the thermopile. For the purpose of the present investigation, however, it is needed to know also the energy values of the light entering the eye. These are sufficiently great only in the case of red and orange to be measured directly with the required precision. It was necessary, therefore, to measure all the wave-lengths used at the objective slit and only the red or orange at the eye, and from the comparative values of the red or orange at the two places to determine a correction factor which will represent for all the colors the reduction of the light from objective slit to eye. In order to determine this reduction factor with precision a larger area of receiving surface of the thermopile had to be exposed to the light than the actual area of the image entering the eye for the threshold determinations. It will be remembered that the height of the objective slit and consequently the height of the image focussed on the pupil of the eye was adjustable. In the present work the receiving surface of the pile used to measure the light at the eye was 11.2548 × .895 mm., or 10.073 sq. mm. The value of 1 mm. deflection of the galvanometer for this area of receiving surface was 88×10^{-10} watt. Since the focussed image is of uniform density, the energy for the area of the image at the eye, 3.7326 mm. × .6956 mm., or 2.5967 sq. mm., could be readily determined. From these values a single factor was calculated which would convert the amount of energy for the different wave-lengths measured at the objective slit into the amounts of energy entering the eye. These values are given in Table V. A division of these values by 2.5967 will give the energy density at the eye, a division by 78.54 the energy density at the stimulus opening.

TABLE V

Red	655 μμ	= 300	× 10^{-9}
Orange	616 μμ	= 133	"
Yellow	580 μμ	= 16.2	"
Yellow-green	553 μμ	= 24.8	"
Green	522 μμ	= 14.8	"
Blue-green	489 μμ	= 9.86	"
Blue	463 μμ	= 9.19	"

G. The Methods of Observation. The experiments were conducted in a light-tight dark-room, the walls, floor, and ceiling of which were painted black. In the preliminary work it was found that an adaptation period of twenty minutes was sufficient to give constant results in the determination of chromatic thresholds. For the achromatic thresholds a much longer adaptation period was needed. The observer was seated in front of the apparatus, the eye being at the focal length of the lens L_4. To ensure steadiness of position the head was held rigid by means of a wax-coated mouthpiece in which the impression of the teeth had previously been made and hardened. The other eye was lightly bandaged with a black cloth. The determinations were made in ascending and descending series. The edges of the stimulus opening were touched at suitably spaced intervals with luminous paint to enable the observer to take and hold the correct fixation. A rough adjustment of the filters and sectored disc was made until an approximate value of the threshold was obtained, and then a rest period of several minutes was given and the exact value of the threshold accurately determined. In order to prevent a progressive loss of sensitivity from fatigue short rest periods were given after each observation. A number of independent determinations were made of the threshold value for each wave-length.

A similar procedure was employed for the determination of the achromatic threshold for each wave-length. In this case, however, even greater care had to be exercised to guard against progressive loss of sensitivity.

IV

STATEMENT AND DISCUSSION OF RESULTS

A. Achromatic Thresholds. The achromatic thresholds of the seven wave-lengths were determined for twenty-one observers. A complete statement of the results is given in Table VI, Parts A and B. A graphic analysis of Table VI is given in Figures VI–XIV.

The minimum visible for the different wave-lengths used was found to be as follows:

1. Red (655 μμ)	Average =	626.99	watt × 10^{-16}
	Median =	637.67	"
	Range =	1209.27 — 186.48	"
2. Orange (616 μμ)	Average =	130.28	"
	Median =	118.08	"
	Range =	273.77 — 70.72	"
3. Yellow (580 μμ)	Average =	27.96	"
	Median =	25.74	"
	Range =	49.04 — 11.56	"
4. Yellow-Green (553 μμ)	Average =	2.203	"
	Median =	2.298	"
	Range =	3.242 — .718	"
5. Green (522 μμ)	Average =	1.953	"
	Median =	1.868	"
	Range =	3.469 — 1.295	"
6. Blue-Green (489 μμ)	Average =	8.11	"
	Median =	8.00	"
	Range =	13.8 — 2.96	"
7. Blue (463 μμ)	Average =	15.62	"
	Median =	15.00	"
	Range =	29.53 — 6.28	"

The total range of minimum visible of the wave-lengths used is therefore from 1209.27, in the red, to .718 (watt × 10^{-16}) in the yellow-green, a ratio from highest to lowest of 1684.

The average sensitivity of the twenty-one observers was greatest in the green. The average threshold for this wave-length is 1.953 (watt × 10^{-16}). There is not, however, complete uniformity as to the position of maximum sensitivity. Nine observers show a maximum sensitivity in the yellow-green. Part A of Table VI gives the results of those whose maximum sensitivity

TABLE VI

ACHROMATIC THRESHOLDS

Amount of light entering the eye (watt × 10^{-16})

No. Observer	Red	Orange	Yellow	Yellow-Green	Green	Blue-Green	Blue
			A				
1. M.M.M.	922.41	103.53	45.74	2.208	1.405	9.58	15.23
2. L.M.	787.50	192.70	11.56	3.145	1.981	10.97	25.95
3. Md.B.	753.63	70.72	44.61	2.596	1.471	11.25	16.37
4. M.B.	689.28	91.14	32.13	2.107	1.295	3.83	8.16
5. E.C.	667.50	129.52	35.06	3.242	2.446	7.16	19.55
6. V.L.	648.83	217.17	35.53	3.220	1.868	8.00	11.06
7. L.L.S.	637.67	273.77	25.74	2.665	1.722	7.74	16.00
8. J.G.L.	626.22	106.24	31.08	2.586	2.116	8.46	14.14
9. M.O.L.	613.90	136.22	21.94	3.024	1.939	7.65	23.32
10. E.C.L.	609.84	123.17	49.04	2.512	2.268	10.50	18.31
11. T.W.L.	498.96	141.90	23.08	1.661	1.513	6.04	20.56
12. Md.B.L.	461.16	115.64	28.73	2.298	2.059	9.91	8.90
Mean—A	659.74	141.76	32.02	2.605	1.840	8.42	16.46
Median—A	643.25	126.35	31.61	2.591	1.904	8.23	16.18
			B				
13. J.G.	1209.27	118.08	25.56	2.480	3.450	8.26	15.06
14. T.W.	787.20	176.08	21.83	1.293	1.353	11.17	13.18
15. M.MC.	642.33	108.10	32.06	2.264	2.539	5.07	11.04
16. E.B.	641.28	88.20	20.74	.818	1.548	6.36	12.20
17. M.G.R.	597.00	119.36	21.14	2.203	3.060	13.80	23.19
18. M.O.	593.45	98.42	29.52	2.550	3.469	10.66	29.53
19. R.N.	305.71	135.42	14.38	1.622	1.718	7.79	13.00
20. E.B.L.	287.30	79.72	18.18	.718	1.395	2.95	7.07
21. H.K.	186.48	111.55	19.66	1.066	1.416	3.10	6.28
Mean—B	583.34	114.99	22.56	1.668	2.216	7.68	14.51
Median—B	597.00	111.55	21.14	1.622	1.713	7.79	13.00
Mean—A and B	626.99	130.28	27.96	2.203	1.953	8.11	15.62
Med.—A and B	637.67	118.08	25.74	2.298	1.868	8.00	15.00

lies in the green, Part B the results of those whose maximum sensitivity lies in the yellow-green. With two such distinct types a single measure of the general tendency of the group is misleading—the mean and median of the two groups were therefore calculated separately. As shown by these measures, the two types are quite different not only with regard to the position of maximum sensitivity but also with regard to the absolute value of the thresholds. With the exception of the green, the average threshold values of the yellow-green type are smaller than those of the green type. There is, however, on the whole, a wider range of values in the yellow-green type than in the green type.

In order to show more clearly the difference between these two groups, as well as to show the relative average sensitivity throughout the spectrum, the results of Table VI, A and B, were plotted in the form of sensitivity curves. The reciprocal of the energy value was taken as a measure of the sensitivity. The maximum sensitivity for each observer was then made equal to unity and the other six values for the observer calculated as ratios of that value. Figure VI is the composite of the twenty-one sensitivity curves. In this composite we can distinguish not only the two groups under discussion, but a possible third group. Two observers, although belonging to the type having maximum sensitivity in the yellow-green, are also very sensitive to green, as is indicated by the great breadth of the curve between wave-lengths 522 $\mu\mu$ and 553 $\mu\mu$. Similarly a few observers belonging to the type having maximum sensitivity in the green are very sensitive in the yellow-green. It is possible that the true maximum in both these

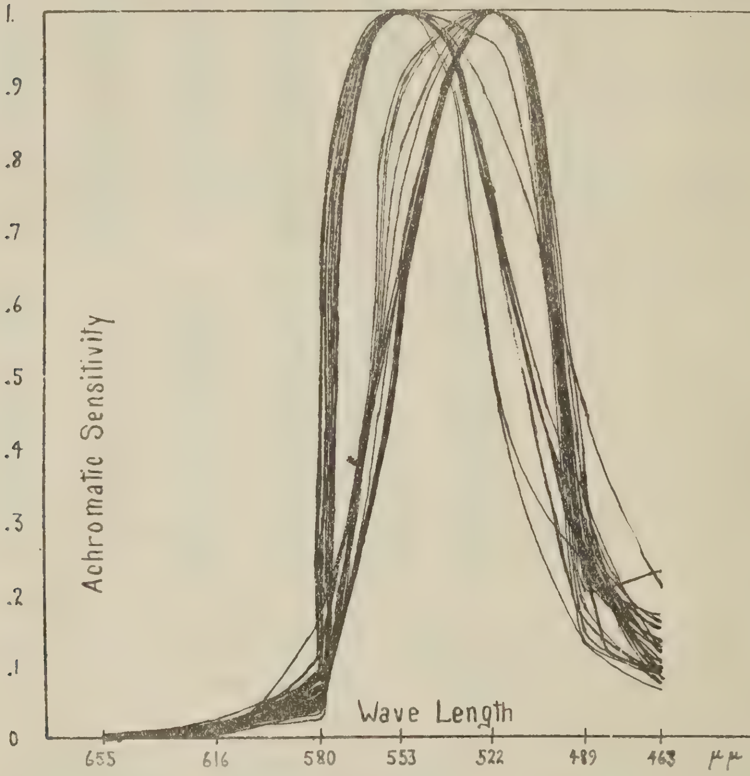


FIGURE VI

cases may be neither green nor yellow-green, but some intermediate wave-length. If the investigation in hand had been for the purpose of determining the exact shape of the threshold visibility curve for all types of observers, the region between 522 $\mu\mu$ and 553 $\mu\mu$ would have been carefully explored for all cases differing from the average in this way. The purpose of the study was, as has been stated, the determination of the minimum visible at certain representative points throughout the spectrum. The possibility of a third type is offered, therefore, merely as a suggestion as yet unproved.

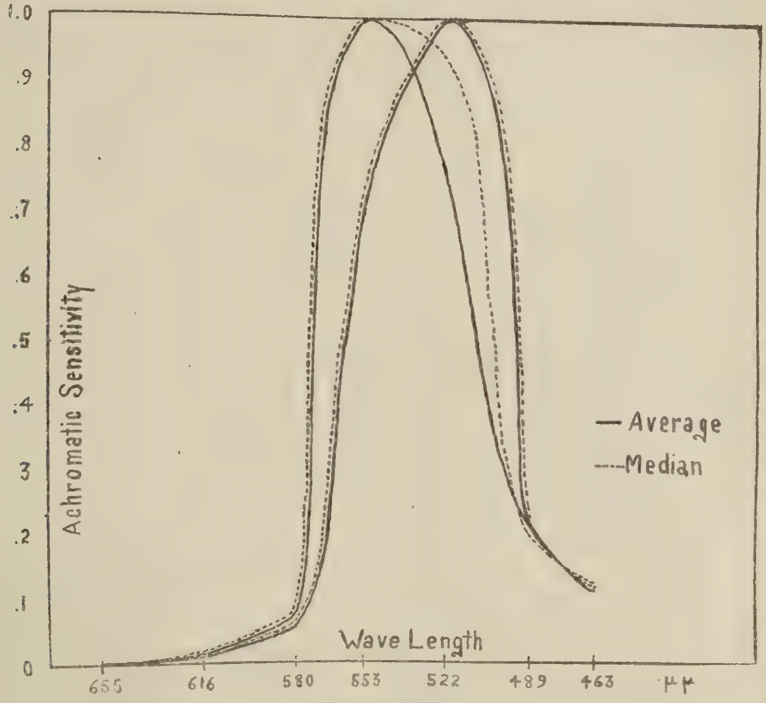


FIGURE VII

The mean and median values of the two groups were also calculated in the form of ratios of sensitivity. Figure VII gives these average sensitivity curves. The curves for the median and mean values agree very closely for the green type, and also for the yellow-green type except in wave-length 522 $\mu\mu$.

For all the wave-lengths employed the distribution of values around the average is approximately symmetrical. The frequency graphs for the seven parts of the spectrum used are given in Figures VIII–XIV. The size of the class interval for the vertical coördinate, representing the number of observers, is the same in all the curves. That along the horizontal coördinate differs according to the absolute value of the minimum visible in the particular color. Thus in red, where the value of the minimum visible is large, the interval is 400 (watt × 10^{-16}), while in green it is only .8 (watt × 10^{-16}). The intervals were further chosen so that the median threshold value of the group in question would fall approximately at the center of some interval. Since the number of observers was small, it was thought that a truer picture of the distribution of values was obtained by the use of rather large intervals. As has been said, the frequency graphs are very nearly symmetrical—each shows a large average group and two smaller, almost equal groups, one superior, one

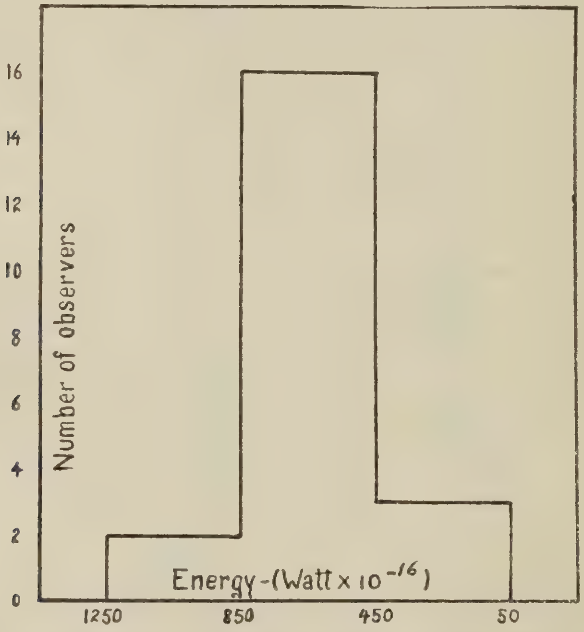


FIGURE VIII. Distribution of threshold values for red, λ 655 $\mu\mu$ (Table VI) inferior to the average. Since this is true even for a small group, it seems reasonable to suppose that the same would be

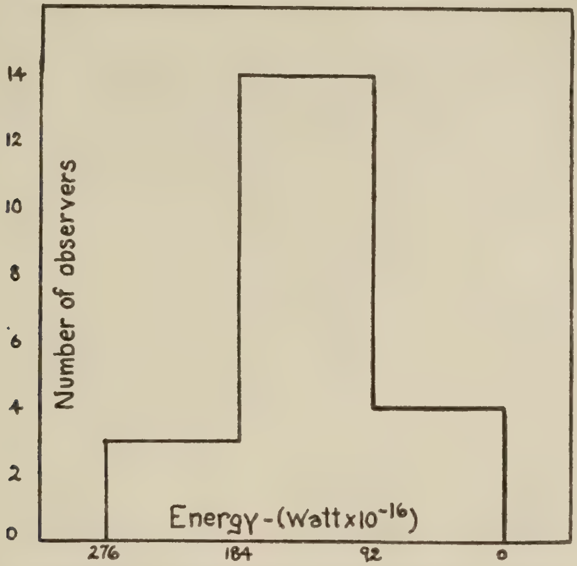


FIGURE IX. Distribution of threshold values for orange, λ 616 $\mu\mu$ (Table VI)

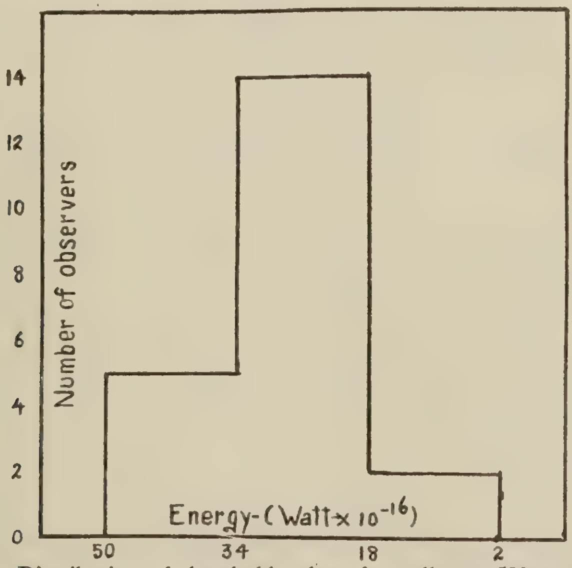


FIGURE X. Distribution of threshold values for yellow, λ 580 $\mu\mu$ (Table VI) true for normal observers as a whole. In other words, it is probable that there is no uniform "normal" sensitivity to light of different wave-lengths, but a very wide range of sensitivity within which an individual threshold may be considered normal.

B. Chromatic Thresholds. It was originally hoped to determine the chromatic and achromatic thresholds of the seven wave-

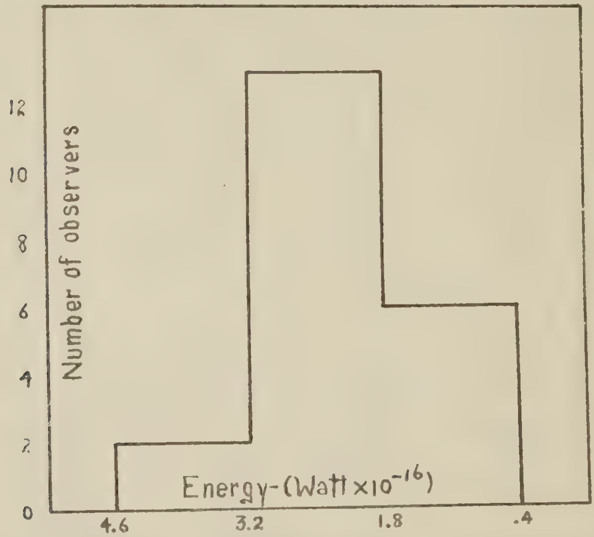


FIGURE XI. Distribution of threshold values for yellow-green, λ 553 μμ (Table VI)

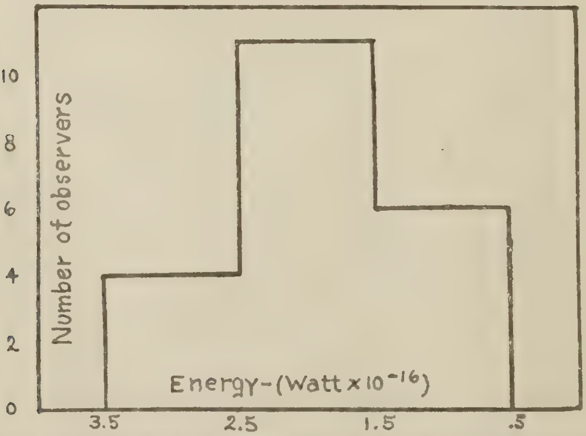


FIGURE XII. Distribution of threshold values for green, λ 522 μμ (Table VI) lengths for the same observers. Most observers, however, were unable to give the time required for this, and comparison is possible, therefore, only between averages. The values of the chromatic thresholds obtained are given in Table VII. Since in only a few cases did the same observer determine the chromatic threshold for all seven wave-lengths, each column of Table VII gives the twenty-one values obtained arranged not according to

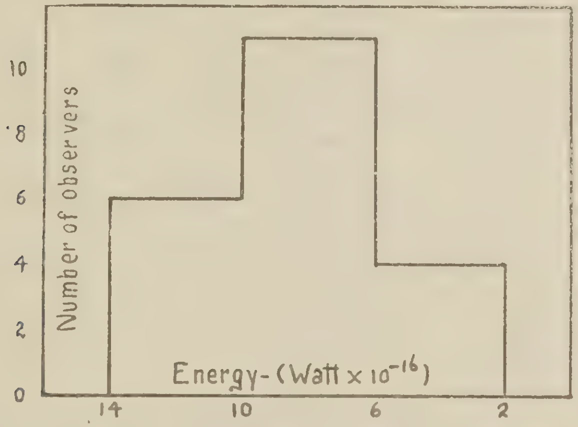


FIGURE XIII. Distribution of threshold values for blue-green, λ 489 $\mu\mu$ (Table VI)

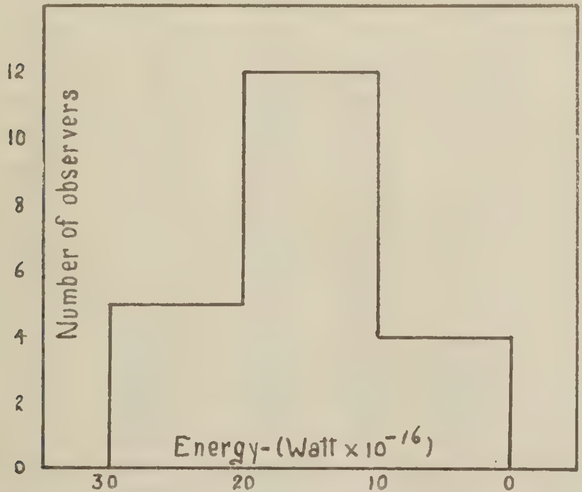


FIGURE XIV. Distribution of threshold values for blue, λ 463 $\mu\mu$ (Table VI) observers, but according to order of magnitude. The results are presented graphically in Figures XV–XXIII.

The minimum visible—chromatic—for the different wavelengths used was found to be as follows:

1. Red (655 μμ) Average = .1778 watt × 10^{-12}
Median = .159 "
Range = .460 — .0597 "
2. Orange (616 μμ) Average = .562 "
Median = .166 "
Range = 3.11 — .054 "
3. Yellow (580 μμ) Average = 9.57 "
Median = 4.32 "
Range = 52.8 — .190 "
4. Yellow-Green (553 μμ) Average = .0856 "
Median = .0127 "
Range = .621 — .00771 "
5. Green (522 μμ) Average = .143 "
Median = .0436 "
Range = .603 — .0042 "
6. Blue-Green (489 μμ) Average = .643 "
Median = .460 "
Range = 3.16 — .0299 "
7. Blue (463 μμ) Average = .812 "
Median = .329 "
Range = 3.07 — .0298 "

TABLE VII

Chromatic Thresholds

Amount of light enternig the eye (watt × 10^{-12})

No.	Red	Orange	Yellow	Yellow-Green	Green	Blue-Green	Blue
1.	.460	3.11	52.8	.621	.603	3.16	3.07
2.	.370	2.44	49.5	.413	.587	2.91	2.54
3.	.316	1.84	38.9	.299	.504	.986	2.48
4.	.301	.833	11.3	.0968	.401	.925	2.32
5.	.228	.820	8.57	.0959	.398	.714	1.32
6.	.188	.522	7.31	.0870	.0859	.548	1.14
7.	.171	.432	7.07	.0268	.0684	.504	.814
8.	.168	.242	6.09	.0148	.0493	.482	.566
9.	.167	.227	4.95	.0142	.0474	.473	.433
10.	.163	.170	4.61	.0130	.0449	.460	.355
11.	.159	.166	4.32	.0127	.0436	.460	.329
12.	.155	.163	.998	.0125	.0429	.366	.284
13.	.129	.149	.896	.0119	.0420	.351	.274
14.	.127	.135	.596	.0117	.0344	.343	.257
15.	.117	.118	.546	.0108	.0218	.321	.252
16.	.101	.0931	.519	.0107	.00818	.299	.233
17.	.100	.0859	.516	.0100	.00628	.0477	.213
18.	.0999	.0786	.516	.00959	.00497	.0473	.0574
19.	.0832	.0667	.463	.00890	.00449	.0404	.0425
20.	.0715	.0568	.461	.00853	.00420	.0321	.0392
21.	.0597	.0540	.190	.00771	.00420	.0299	.0298
Mean	.1778	.562	9.57	.08555	.14314	.643	.812
Med.	.1590	.166	4.32	.01270	.04360	.460	.329

The total range of the chromatic minimum visible of the wave-lengths used is therefore from 52.8 in the yellow to .0042 (watt × 10^{-12}) in the green, a ratio from highest to lowest of 12571.

The average chromatic sensitivity is greatest in the yellow-green. The average threshold value for the yellow-green is .08556 (watt × 10^{-12}). The relative sensitivity to the other wave-lengths is best shown by Figure XV, which gives the mean and median values in the form of sensitivity curves. These curves were plotted in the same way as those in Figure VII. In both the mean and median sensitivity curves there is an extremely sharp drop from the yellow-green to the yellow. Since the chromatic thresholds for all colors were not determined throughout on the same observers, a composite of the individual sensitivity curves, similar to the composite of achromatic sensi-

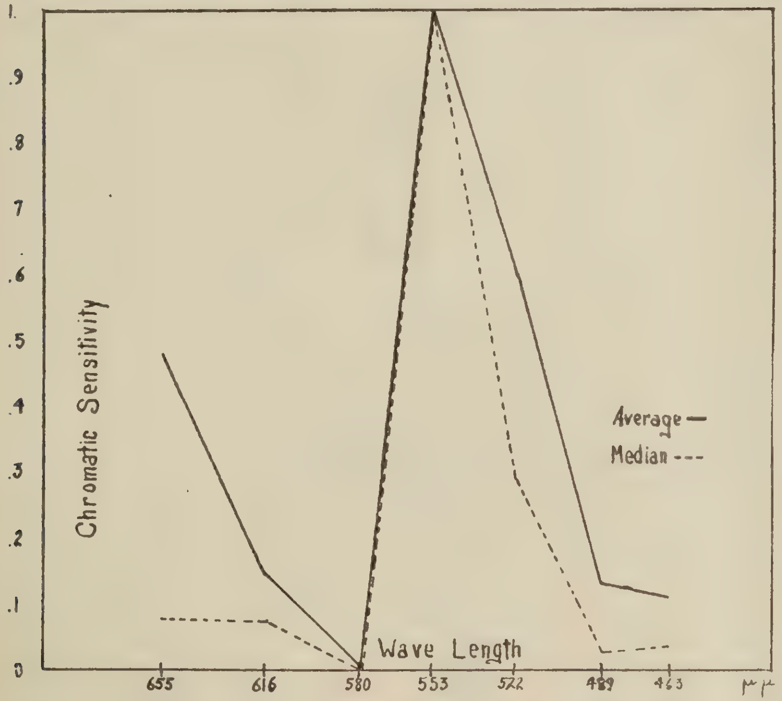


FIGURE XV

tivity curves could not be made. All seven thresholds, however, were determined for six observers, and a composite of their sensitivity curves is given in Fegure XVI. There is much more variation in these curves than in those representing achromatic sensitivity. Four only have a maximum sensitivity in the yellow-green; of the other two, one shows a maximum in the green, the other in the blue. The relative sensitivity to the longer wavelengths is more uniform—all six curves show the drop in the yellow, and all are fairly close together in the orange and red.

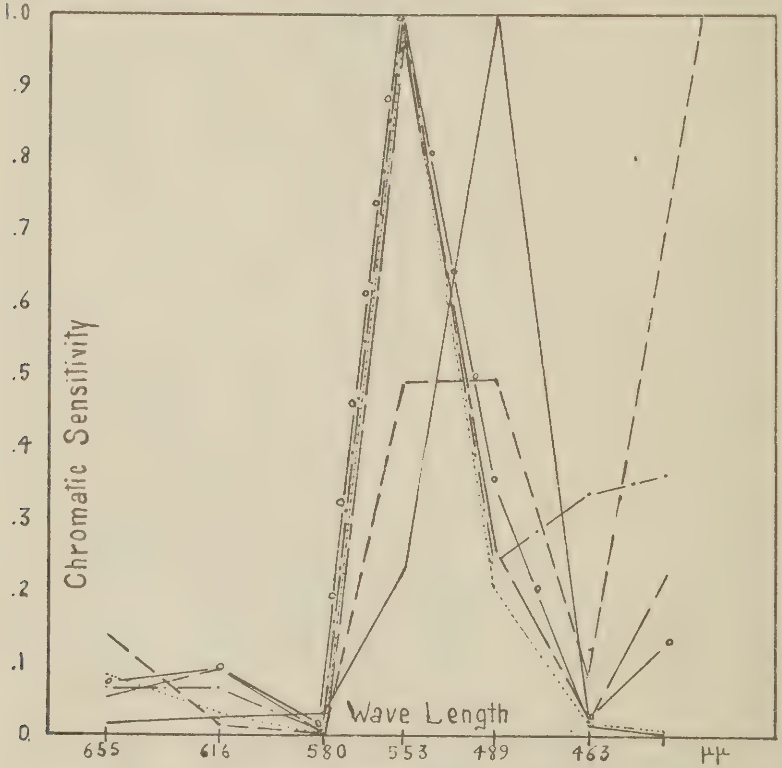


Figure XVI

For the observers tested, the distribution of chromatic threshold values around an average is not symmetrical. In each color the threshold value of the median is much smaller than that of the corresponding average—that is to say, the curves are skewed to the upper end. This means that the range of values below the median is much greater than that above the median. For instance, there is a difference of 48.48×10^{-12} watt between the

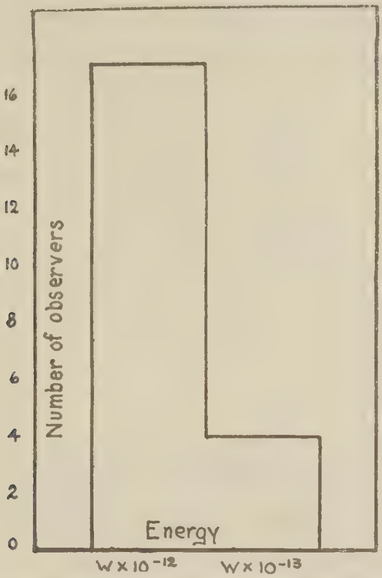


FIGURE XVII. Showing the threshold values for red, λ 655 μμ (Table VII)

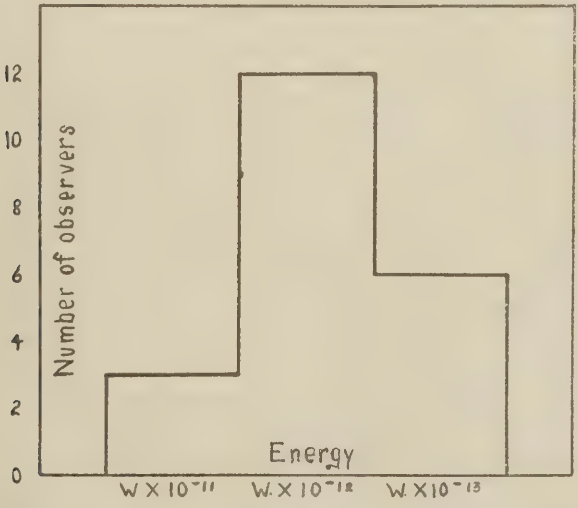


FIGURE XVIII. Showing the threshold values for orange, λ 616 μμ (Table VII) median and the largest threshold in yellow, while there is a difference of only 3.13 between the median and the smallest threshold value in the same color. Because of this very wide range it was thought advisable to plot the logarithms of the energy values of

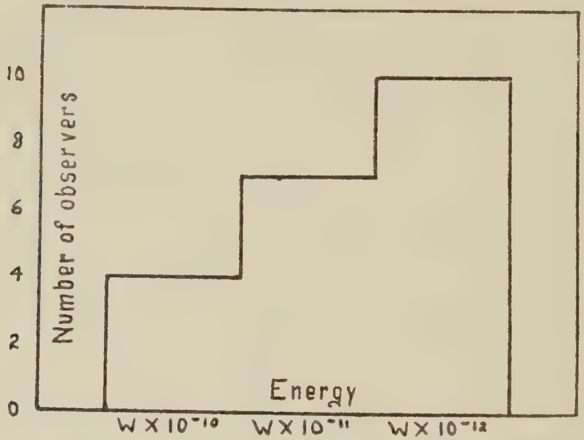


FIGURE XIX. Showing the threshold values for yellow, λ 580 $\mu\mu$ (Table VII)

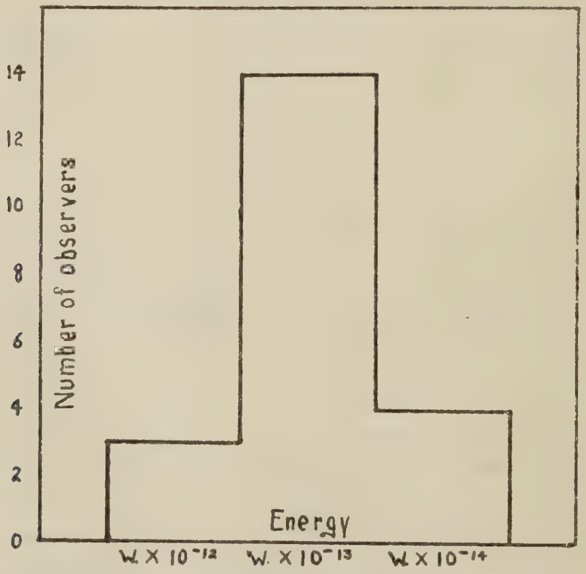


FIGURE XX. Showing the threshold values for yellow-green, λ 553$\mu\mu$ (Table VII) the chromatic thresholds rather than the values themselves. Figures XVII–XXIII shows the frequency graphs of the seven wave-lengths. Along the ordinates is plotted number of cases. As in the curves for achromatic sensitivity, the class interval

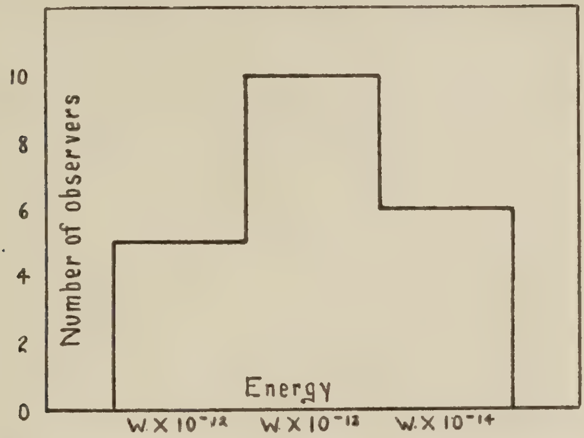


FIGURE XXI. Showing the threshold values for green, λ 522 μμ (Table VII)

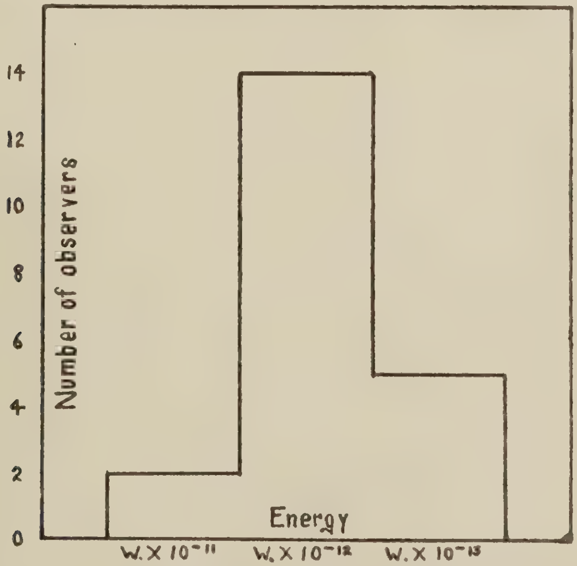


FIGURE XXII. Showing the threshold values for blue-green, λ 489 μμ (Table VII) for the abscissae differs for the wave-lengths. Thus the first interval of the abscissa in blue-green, blue and orange contains all cases of the order 10^{-11} watt, the second interval all cases of the order 10^{-12} watt, and the third all cases of the order 10^{-13} watt. In green and yellow-green the intervals contain cases of the orders 10^{-12}, 10^{-13}, and 10^{-14} watt, respectively, and in the yellow 10^{-10}, 10^{-11}, and 10^{-12} watt.

It will be noted that the graphs of red and yellow differ from those of the other five wave-lengths by showing skewness even in their logarithmic form. In red there is no inferior group—the values fall into a large average group and a smaller superior group. In yellow there is no superior group, but there is an additional very inferior group. It might seem reasonable to account for this on experimental grounds because of the difference in the abruptness with which the chromatic component comes into the sensation in the two cases. The chromatic threshold for red is by far the easiest to determine. The transition from achromatic to chromatic is abrupt and sharply marked and there is little or no hesitation on the part of the observer as to whether or not there is any color present. The ease of judgment resulting from this small and clearly defined transition interval probably

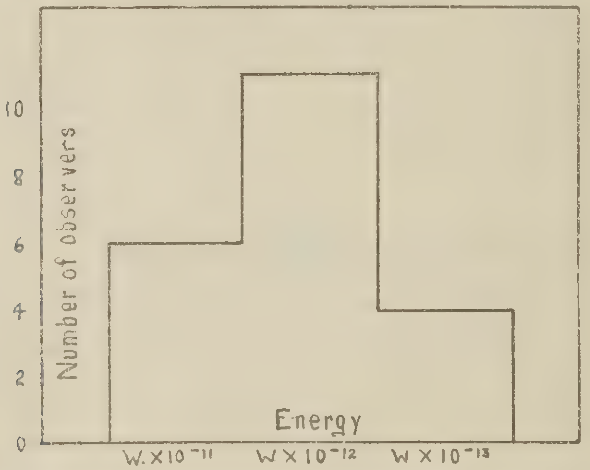


FIGURE XXIII. Showing the threshold values for blue, λ 463 $\mu\mu$ (Table VII) accounts for the absence of the inferior group. In yellow just the opposite condition obtains. The color comes in very slowly and gradually and the exact point of appearance of the chromatic component is difficult to determine. At low intensities light of wave-length 580 $\mu\mu$ has much the appearance of ordinary artificial light, such as that emitted by a carbon lamp, which an unpracticed observer is accustomed to consider as white. In such a case much greater intensities are needed for the light to be called colored. This may account for the additional very low group in yellow not found in any other of the colors.

C. The Photochromatic Interval. By the photochromatic interval is meant the colorless interval between the chromatic and the achromatic thresholds. In the present study the actual energy of both thresholds has been measured. This makes it possible to express the value of the photochromatic interval in absolute terms—terms that admit of a numerical comparison from wave-length to wave-length. Previous to this the photochromatic interval has been discussed only in the most general terms. Its existence, and the fact that it varied under different conditions, were noted by Tschermak (11), Fick (12), v. Kries (13), Hering (14), and others. There has been only one numerical statement of the value of the colorless interval between the two sets of thresholds, that of Charpentier in 1888 (15). Charpentier focussed light from the spectrum of the sun on ground glass, using the colored surface thus obtained as the stimulus for his determinations. The intensity was reduced by a diaphragm. No measurement, either photometric or radiometric, was made of the actual intensities used. The relation between the chromatic and achromatic thresholds was taken as equal to the ratio of the square of the diameters of the diaphragm openings necessary for the two thresholds at any given wave-length. The diameter of the opening required to reduce light in the yellow to the achromatic threshold was 1, the opening for the chromatic threshold of the same color was 3.1. The chromatic threshold is then, according to Charpentier, 9.6 times as large as the achromatic threshold. The ratios found are as follows:

Rouge extreme	3.6
Orangé	5.5
Jaune	9.6
Vert moyen	196.0
Bleu franc, région moyenne	635.0

The wave-length is not stated. Such ratios, obtained without reference to the absolute or even the relative intensity of the lights used, have little value other than to indicate that there is a photochromatic interval.

In 1892 Abney and Festing (16) determined the achromatic and chromatic thresholds throughout the spectrum and attempted to give a photometric evaluation to the results obtained. A monochromatic beam and a comparison white beam were so reflected as to fall on adjoining portions of a white screen. The chromatic thresholds were determined by reducing the intensity by means of a sectored disc introduced into the path of the monochromatic beam. Relative luminosity values were calculated by the use of a spectrum luminosity curve previously obtained. Relative luminosities, however, change with change in intensity of light, and this curve, while a low intensity curve, was not determined for threshold intensities. Achromatic thresholds were similarly determined, the relative luminosities of the different wave-lengths being calculated from the sectored disc values and the luminosity curve just mentioned. Abney and Festing did not, however, attempt to assign any values, either relative or absolute, to the photochromatic interval as such, and since their values for the thresholds are only relative, it is not possible to calculate it from their data.

The values of the photochromatic interval for the seven wave-lengths used in this study are shown in Table VIII. Column 2 gives the energy value of the minimum visible achromatic, column 3 that of the minimum visible chromatic, and column 4 the difference between the two. In column 5 the values of column 3 are given in the form of ratios, the value for yellow being made equal to unity. The values are very large, ranging from 853.29×10^{-16} watt in the yellow-green to 95672.04×10^{-16} watt in the yellow. There is, apparently, a great difference between the development of the color sense of the eye and that of the light sense.

TABLE VIII

Wave length	Achromatic T. (watt × 10^{-16})	Chromatic T. (watt × 10^{-16})	Difference (watt × 10^{-16})	Ratio Yellow = 1
655 μμ	626.99	1778.00	1153.00	.01
616 μμ	130.28	5620.00	5489.72	.06
580 μμ	27.96	95700.00	95672.04	1.00
553 μμ	2.203	855.50	853.30	.009
522 μμ	1.953	1431.40	1429.45	.02
489 μμ	8.11	6430.00	6421.89	.07
463 μμ	15.62	8120.00	8104.38	.08

The value of the photochromatic interval throughout the spectrum is represented graphically in Figure XXIV. Along the vertical coördinate are plotted energy values (watt × 10^{-16}). The resulting curve bears to some extent an inverse relation to the curve of chromatic sensitivity. Thus, the greatest chromatic sensitivity being in the yellow-green, the smallest photochromatic interval is in the yellow-green; similarly the largest photochro-

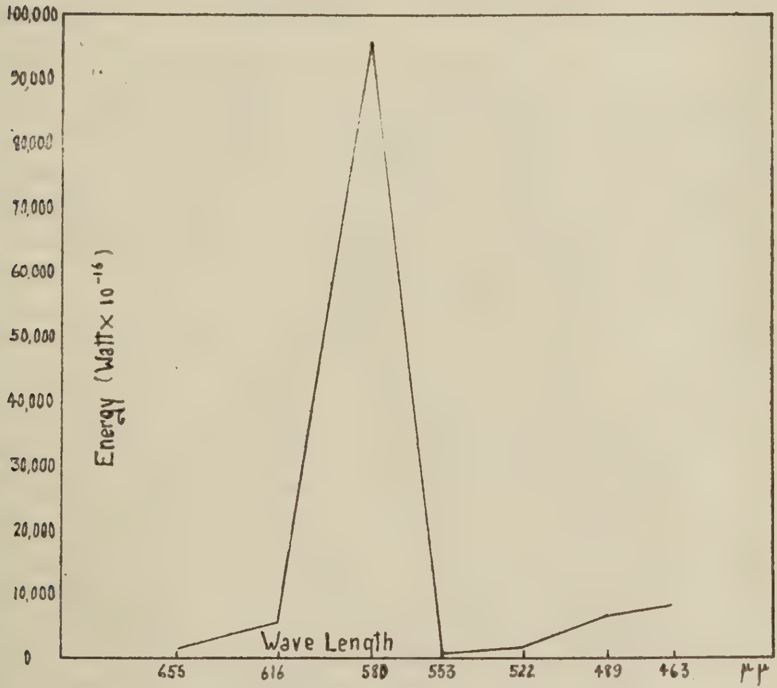


FIGURE XXIV. Showing value of the photo-chromatic interval (Table VIII) matic interval is in the yellow, to which there was the least chromatic sensitivity.

D. Comparison with Previous Determinations of the Threshold Visibility Curve. In section II is given a summary of various investigations that have been made of the relative sensitivity of the eye to lights of different wave-lengths. In no case was the apparatus and procedure identical with that employed in the present study, but it is, however, of interest to make the general comparison between such curves and the curves presented here. Figure XXV shows graphically a comparison of the results of Ebert, König, Langley, and the two types found in this experiment. In each case the maximum sensitivity was made equal to unity. The curve for Ebert represents the average relative sensitivity of two observers. It will be remembered that these two sets of results were very similar. König also gave values for only two observers, and these, too, have been averaged here, since they show comparatively small differences. The curve for Langley is plotted from the results of one observer. The range of maximum of the five curves is from λ 505 to 553 μμ. König's

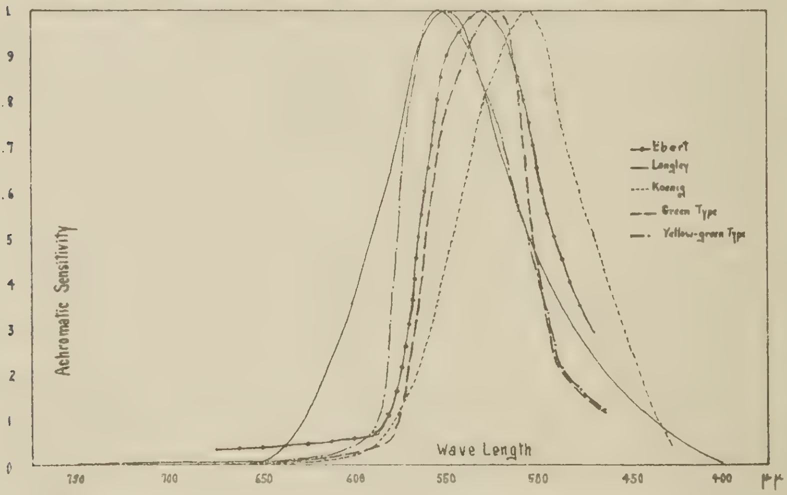


FIGURE XXV. Comparison of results of threshold visibility curve by various observers curve is shifted toward the blue end of the spectrum; Langley's curve, very similar to that of the "yellow-green type" found here, is shifted toward the red end. Ebert's curve and the curve of the "green type" fall between these two extremes. So different were the conditions of experimentation in each case that it would be futile to attempt to analyze disagreements. Difference in source, difference in number (and probably type) of observer, difference in methods of energy determination—any one of these would seem to be sufficient to account for the variation found. Indeed, it is surprising that there should be as much agreement as there is.

It will be noted that the results of Pflüger are not represented on this composite graph. The individual and diurnal variations in Pflüger's results were so large as to make averaging for the purpose of such a comparison impossible. The position of the maximum according to him ranges from λ 495 to 524 $\mu\mu$, and this deviation is found even in the results for a single observer—EI. A portion at least of this extreme variation can be explained. In the preliminary work of the present study the same difficulty obtained. It was soon found, however, that much of this diurnal fluctuation could be traced to physiological factors which could be controlled—at least in part. A cold, lack of sleep, or general fatigue changed the character of the results greatly—not only was the absolute sensitivity lessened, but the relative sensitivity was altered. Table IX gives the threshold values for the same observer taken on different days—once when much fatigued, the other when rested. In many colors the difference amounts to several hundred per cent. Besides being very insensitive, a fatigued observer is erratic, often makes entirely contradictory judgments, and is much more subject to troublesome after-images and idio-retinal light. Curiously enough, general fatigue was found to be more disturbing than eye strain. As has been stated in the section on apparatus and procedure, before making the final threshold determinations each observer was carefully questioned and a few trial settings made as a check on fatigue. It is believed that the influence of this factor on the final results is negligible.

TABLE IX

Condition	Red	Orange	Yellow	Yellow-Green	Green	Blue-Green	Blue
Fatigued	2257.94	676.25	48.67	4.618	4.558	16.00	19.04
Rested	305.71	135.42	14.38	1.622	1.718	7.79	13.00

E. The "Minimum Visible." In the work described in the preceding chapters the amount of light required to arouse both the chromatic and the achromatic response in different parts of the spectrum, the minimum visible for those wave-lengths has been measured directly in energy terms for the first time. As was pointed out in the historical section, the determinations of comparative sensitivity by Ebert, Pflüger, and others were made only in relative terms. Absolute values were not assigned to the light intensities on which the values were based. Moreover, in all cases but one the galvanometer deflections used in compiling the ratios were not obtained with the stimulus actually used in producing the eye's reaction.

Following a different line of development, however, attempts have been made to calculate the energy value of the minimum visible. The photometric and radiometric data used in making these calculations, however, were assembled from different sets of observations and experiments. One of the first of such estimates is that of Wien (17), who in his dissertation, "Ueber die Messung von Tonstärken," 1888, sought to compare the absolute sensitivity of the ear with that of the eye, his data on visibility being taken from the observations of the astronomers. He assumed that brightness of stars of the sixth magnitude could be taken roughly to represent the limit of visibility. By a comparison of available photometric and radiometric data he estimated the light from those stars to have an approximate value of 4×10^{-15} watt.

Drude (18), some eleven or twelve years later, calculating also from stellar data, obtained a smaller value for the minimum visible, 6×10^{-16} watt. He assumed the brightness of a star of the sixth magnitude to represent the limit of visibility, a brightness which he estimated to be equal to that of the Hefner lamp at 11,000 meters. Angström (19) had determined experimentally the energy value of the Hefner unit of illumination (the light emitted in a unit solid angle, the lumen) to be 8.1×10^4 erg/sec. The relation of the unit of illumination to the unit of energy or power Drude called the mechanical equivalent of light. This relation of the photometric to the energy unit has been much employed by later investigators in attempts to arrive at approximate energy values from measurements made in photometric terms. The energy value of the lumen thus, in terms of the Hefner standard, would be 8.1×10^4 erg/sec., and the intensity of the illumination from a Hefner lamp at 11,000 meters would equal 1×10^{-8} lumens per square meter. Assuming further a pupillary opening of 3 mm., Drude calculated:

$$8.1 \times 10^{-8} \times .07 = .6 \times 10^{-8} \text{ erg/sec.} = 6 \times 10^{-16} \text{ w.}$$

This value of Drude has recently been recalculated by Coblentz (20), who had himself measured the total radiation of a Hefner lamp. Coblentz found the light density at 1 meter to be 7×10^{-8} g.cal. (or 29×10^{-8} w) per cm^2 per second. With this value the minimum visible would be:

$$\frac{29 \times 10^{-8} \times .07}{11000^2} = 1.7 \times 10^{-16} \text{ w.}$$

Another calculation of the least radiation visually perceptible from astronomical data is that of Ives (21). Ives, too, accepted the brightness of stars of the sixth magnitude as representing the minimum visible, but recalculated the photometric value of this brightness on the basis of later data on the relation of stellar magnitude to the candlepower scale. He also used a different value of the mechanical equivalent to convert the photometric into radiometric terms. Drude had based his determination of the mechanical equivalent on the lumen as representing the total radiation in a solid angle from the Hefner standard. Ives used the lumen to represent the photometric unit of radiation from the region of the visible spectrum to which the eye is the most sensitive, taken from previous determinations of the relative sensitivity of the eye to wave-length. These determinations, however, were not made at threshold intensities. If the minimum visible be taken to represent the least amount of radiation visually perceptible, of wave-lengths to which the eye is most sensitive, the lumen selected by Ives is the more compatible with the purpose of the problem. However, the light selected by Drude on which to base the ratio of the photometric to the radiometric unit is more nearly of the same composition as the light used to produce the eye's reaction. Both methods are in error, but on different points. Obviously if the minimum visible is to be determined in absolute units for the wave-lengths to which the eye is most sensitive, these wave-lengths should be used to determine the threshold of sensation and the energy value of the light should be measured directly. Using .00159 as the lumen value in watts, Ives made the following calculation:

1 meter-candle = 1 lumen per sq. meter = 0.0001 lumen per sq. cm. = .000000159 watt per sq. cm. = 1.59 ergs per sec. per sq. cm.

The meter-candle value of a star of the sixth magnitude had been found by Russell to be 0.849×10^{-8}. Ives, adopting this value, obtained

$$1.59 \times 0.849 \times 10^{-8}\ \text{w} = 1.35 \times 10^{-8}\ \text{erg/sec.}$$

Assuming a 6 mm. pupillary opening instead of a 3 mm. opening, the minimum visible would equal

$$.38 \times 10^{-8}\ \text{erg/sec.} = 38 \times 10^{-17}\ \text{w.}$$

Russell (22), supplementing the work of Ives, adopted the same method of calculation, but used what he thought to be more correct figures for the breadth of the pupillary aperture and the stellar magnitude of the faintest visible object. He accepted the pupillary value of 8.5 mm. proposed by Steavenson and a stellar magnitude of 8M.5. The resulting minimum visible was 7.7×10^{-17} w.

The above method of calculating by means of stellar data and the mechanical equivalent has been varied by the use of an artificial star. In this way the photometric determination of the threshold can be made experimentally, thus avoiding to some extent the uncertainties of stellar observations. Buisson (23) measured the distance at which phosphorescent screens of different sizes could just be seen. The brightness of the screen was then transmuted into the stellar magnitude scale. Using the same values for the mechanical equivalent and pupillary aperture as did Ives, he found the minimum visible to be 12.5×10^{-17} w. Reeves (24) used the transmitted light of a modified Nutting sensitometer, the intensity of which could be controlled. The source of light was a tungsten lamp. He also measured the pupils of his observers instead of taking a standard average value. With a visual angle of 1.17 (1 mm. star at 3 meters), the total energy entering the eye at threshold intensity was calculated to be 19.5×10^{-17} w. (mean of three observers). The mechanical equivalent was taken equal to .00159 watt per lumen.

Among the investigation in which some magnitude of star is assumed as the limit of visibility, direct energy measurements of that source have been made only in one case. Coblentz (20) assumed stars of the sixth magnitude to have the least visible brightness and measured directly the visible radiation from these stars. He states his procedure briefly as follows: " The sensitivity of the eye may be estimated—from direct measurements of the heat from stars. The calibration of the radiometer was 1 mm. deflection $= 34 \times 10^{-14}$ g.-cal. per cm.^{2} per minute $= 85.5 \times 10^{-16}$ w. per cm.^{2} per second. The sixth magnitude stars gave deflections of 0.5 mm. for blue stars to 1.5 mm. for red stars (say, 1 mm. on an average), depending on their color. From measurements made on the transmission of stellar radiation through a cell of water the radiant luminous efficiency may be 0.2 (0.1 for red stars to 0.4 for blue stars). Hence the luminous energy intercepted by a pupillary opening of 0.07 cm.^{2} is $(85.5 \times 10^{-16} \times 0.2 \times 0.07) = 1.2 \times 10^{-16}$ w." Here, then, is a direct radiometric measurement of the source—there is, however, no corresponding direct determination of the threshold.

The above summary of work done by previous investigators shows disagreement both as to procedure and as to what shall be called " the least radiation visually perceptible " or " the minimum visible." Lights differing greatly in composition have been used, spectrum and approximate white; and with one exception the energy value has been calculated indirectly from measurements made on some other source or computed by the use of a mechanical equivalent which expresses the relation of the photometric to the energy unit for some other source than the one used for the visual stimulus. And in case of this one exception the limit of visibility was taken from astronomical data on the visibility of stars, the estimates of which range from the sixth to the eighth magnitude, rather than having been experimentally determined.

It would seem reasonable to assume that *the* minimum visible should mean the least amount of radiation visually perceptible of the wave-length or range of wave-lengths to which the eye is the most sensitive measured in absolute units. So defined, the essential conditions for its determination would be a careful search of the spectrum for this wave-length to which the eye is the most sensitive, a determination of the limit of visibility with this wave-length, and the direct measurement of its energy. In the investigations cited above, one and sometimes two, but never all of these conditions, have been satisfied. Moreover, in no case, whatever the source of light chosen, has the energy been measured and an actual determination of the limit of visibility been made for the same light.[1]

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[1] By a still more rigid interpretation the determination of the minimum visible might also involve the satisfying of other and more difficult requirements such as the use of the most favorable time of exposure and size of field, the use of the most sensitive part of the retina, etc., all of which features would in all probability differ in value both for the wave-length of light employed and for the observer. Von Kries and Eyster (25) sought to determine the achromatic threshold not only with the wave-length to which the eye is most sensitive but also under the most favorable conditions of time of exposure, size of field and portion of the retina used. Their selection of 507 $\mu\mu$ as the proper stimulus to use was apparently based not on a determination of their own of relative sensitivity but primarily on the fact that Trendelenburg had found that this part of the spectrum gave the maximum bleaching of the visual purple. According to the Düplicitäts theory the wave-length that would give the maximum bleaching of the visual purple should be theoretically the most correct. Also this wave-length fell within the range to which König had found the eye to be the most sensitive for a group of observers. Their description of procedure leaves one in doubt whether the long and exceedingly difficult systematic survey was made which would be needed to determine what part of the retina is the most sensitive to the light in question, and what is the optimum size of field and time of exposure. The statement is made that the periphery of the retina was used and that several sizes of field and times of exposure were used, but no information is given

The determination of the minimum visible has been by no means the purpose of the present investigation. The energy values of the achromatic and chromatic thresholds have been determined for seven representative parts of the spectrum. There has not been a graded, minute search for the wave-lengths to which the eye is the most sensitive. However, two of the points used, $522\ \mu\mu$ in the green and $553\ \mu\mu$ in the yellow-green, fall within the range of wave-lengths to which previous investigators have found the eye to be the most sensitive at threshold intensities for different types of observers. To this extent the requirement that in the determination of the minimum visible the wave-length should be used to which the eye is the most sensitive at the threshold intensities has been satisfied; the other requirement, that the energy measured should be of the light used to produce the eye's reaction, has been fully satisfied. It would seem then that our results are entitled to consideration together with those purporting to represent the minimum visible, although such a determination formed no part of the original purpose and its relation to the present work came out only in a study of the results obtained.

A brief summary of the various values that have been obtained is given in Table X in order that the values of previous investigators may be more conveniently compared with those obtained here. The apparent closeness of agreement of the results

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as to the approximate meridian or degree of eccentricity of the area of the retina stimulated. The source of light was a Hefner lamp the radiations from which were reflected from a magnesium oxide surface into a spectroscope. The energy values were calculated from Angström's data on the distribution of energy in the light from a Hefner lamp. Von Kries sums his conclusions as follows:

"1. Für eine merkliche Erregung des Sehorgans ist bei Herstellung der günstigsten Bedingungen hinsichtlich Adaptation, Strahlungsart ($507\ \mu\mu$) räumlicher und zeitlicher Verhältnisse eine Energiemenge von $1{,}3$–$2{,}6 \times 10^{-10}$ Erg. erforderlich.

"2. Für die Sichtbarkeit dauernd exponierter Objekte ergibt sich bei günstigster Strahlungsart und güstigster räumlicher Anordnung eine Energiezuführung von ca. $5{,}6 \times 10^{-10}$ Erg. pro Sekunde."

Boswell (26) repeated the experiments of von Kries and Eyster, using an amyl acetate lamp as source and the fovea rather than the more sensitive peripheral retina. He calculated the minimum visible to be 23.7×10^{-17} watt.

obtained may not at first glance seem compatible with the rather wide disagreement in plan and method of making the determinations. On this point, however, two comments may be made: (a) The percentage disagreement is not small, and (b) a great deal of disagreement is doubtless masked by the insensitivity of the instrument used to measure the energy values as compared with the eye. Coblentz (20), for example, has estimated the eye to have 300,000 times the sensitivity of the thermopile.

TABLE X

Wien	40.00×10^{-16}w	Reeves	1.95×10^{-16}w
Drude	$6.00 \times$ "	Von Kries	$.20 \times$ "
Drude-Coblentz	$1.70 \times$ "	Boswell	$2.37 \times$ "
Ives	$3.80 \times$ "	(Present study)	
Russell	$.77 \times$ "	Average (553 $\mu\mu$)	$2.56 \times$ "
Buisson	$1.25 \times$ "	Average (522 $\mu\mu$)	$2.30 \times$ "
		Smallest value	$.64 \times$ "

F. Pathological Cases. The importance of light and color sense testing as an aid to diagnosis in pathological conditions of the eye is well recognized. There has been, however, little or no quantitative study along this line. Although the present apparatus is, of course, unsuited to clinic work, it was thought of interest to determine the achromatic and chromatic thresholds to certain wave-lengths in a few typical pathological cases.

The following patients were sent me by Dr. Luther C. Peter, Associate Professor of Ophthalmology, Philadelphia Polyclinic and College for Graduates in Medicine, University of Pennsylvania, whom I wish to thank for his kindness both in coöperating in the finding of suitable cases and in furnishing the history of each case.

CASE I

Mr. Charles P., age fifty-six, cabinet maker. Chief complaint dimness of vision. Has been a heavy user of tobacco and alcohol. Vision O D = 20/100, O S = 20/150, plus correction = 20/40 partly in the right and 20/70 in the left eye, now corrected to 20/40 in each eye.

Fundus shows atrophic condition of the optic nerves with low grade retinitis. Fields are considerably contracted for colors, and both blind spots are enlarged for both form and color.

Diagnosis: Toxic amblyopia (tobacco and alcohol); papillo-macular bundle is undoubtedly involved in the toxemia.

Toxic amblyopia—weak vision due to chronic toxemia—may be brought on by any toxic agent, but its chief causes are tobacco and alcohol, either singly or combined. Samelsohn, according to Fuchs (27), was the first to discover the anatomical changes that take place in the disease. "He showed that they were limited to the papillo-macular bundles, whose position and course within the optic nerve he was thus able to determine. In the course of this bundle it is found that the nerve fibers have disappeared and nothing but glia tissue is present, while the connective-tissue septa lying between the nerve fibers are thickened. Samelsohn regarded this as the outcome of an interstitial inflammation of the optic nerve, the inflammation affecting the connective tissue portion and especially the septa which convey the blood vessels and which because of the inflammation become thickened. Others, however, think that thickening of the connective tissue is a primary lesion of the optic-nerve fibers by the poison, and that if a thickening of the connective-tissue septa was found, this was a secondary change. Lastly, there are some who believe that even the destruction of the nerve fibers is not the primary affection, but that, in analogy with the conditions of acute poisoning (by quinine, etc.), this consists in a lesion of the ganglion cells in the retina and that an ascending atrophy develops in the nerve fibers as a secondary affair."

The values of the chromatic and achromatic thresholds obtained are given in Table XI. The loss of sensitivity for both color and light sense is very great. The loss is not, however, uniform throughout the spectrum—there is much irregularity shown from wave-length to wave-length. The extremely insensitive reaction to blue (right eye) and red (left eye) is particularly noticeable.

TABLE XI

TOTAL AMOUNT OF LIGHT ENTERING THE EYE (Mr. Charles P.)

A. Achromatic Thresholds (watt × 10^{-16})

Color		Right	Left	Average (Normal)
Red	(655 μμ)	3754.76	1101394.80	626.99
Yellow	(580 μμ)	433.73	4888.48	27.96
Green	(522 μμ)	27.64	34413.28	1.953
Blue	(463 μμ)	61695.27	2789.47	15.62
B. Chromatic Thresholds (watt × 10^{-12})				
Red	(655 μμ)	.332	297.640	.178
Yellow	(580 μμ)	86.530	9.406	9.570
Green	(522 μμ)	3.820	74.140	.143
Blue	(463 μμ)	156.440	201.430	.812

CASE II

Ruth L., age thirty-eight, single, housework. Bilateral glaucoma when twenty-eight years of age. Present condition of the right eye—phthisis bulbi and blind. Left eye — vision = 20/15 partly. The left eye was operated on twice, first operation about eight years ago, an iridectomy; second operation sclero-corneal trephining about eight months ago. Tension normal.

Fields show some contraction for both form and color. Up and to the nasal side of the field is a large angular scotoma extending from and including the blind spot of Mariotte to the periphery including about 1/6 of the circumference of the field. The blind area passes in a horizontal line above the point of fixation. The macular fibers are not involved by the pathologic process in so far as clinical methods can determine.

Diagnosis: Chronic congestive glaucoma; partial loss of the upper nasal field.

The threshold values for the left eye are given in Table XII. Chromatic sensitivity is normal and the achromatic threshold for green is normal; the achromatic sensitivity to red and blue, however, is very low. The threshold values for yellow were not determined, as the eye fatigued rapidly.

TABLE XII

Total Amount of Light Entering the Eye (Ruth L.)

A. Achromatic Thresholds (watt × 10^{-16})

Color		Left	Average (Normal)
Red	(655 μμ)	2871.54	626.99
Green	(522 μμ)	3.32	1.953
Blue	(463 μμ)	70.15	15.62
		B. Chromatic Thresholds	(watt × 10^{-12})
Red	(655 μμ)	.287	.178
Green	(522 μμ)	.407	.143
Blue	(463 μμ)	.687	.812

CASE III

Mr. Wm. A. M., age fifty-one, carpenter. Eyes have been failing for seven years. Hypermature cataract in the right eye, incipient cataract in the left. In addition the patient is suffering from bilateral sclerosis of the choroid. Patient has tubular vision in the left eye, 20/30 partly, central vision, improved to 20/20; vision now reduced to 20/40. Light perception only in right eye. Form fields are reduced to 10° in the left eye, and red and green varies from between 5° and 7°. Light perception and light projection is feebly present to the extent of 20°. Wassermann is positive. Clinical diagnosis—sclerosis of the choroid and incipient cataract.

The threshold values obtained are given in Table XIII. Both eyes are much below normal, the right more so than the left, as would be expected. In this case again the relative sensitivity is quite different from that of the normal eye—sensitivity to blue being disproportionately low. The chromatic responses are most erratic, although they approach the normal more nearly than do the achromatic. In these, too, is shown the great loss of sensitivity to blue.

TABLE XIII

Total Amount of Light Entering the Eye (Mr. W. A. M.)

Color		Right	Left	Average (Normal)
A. Achromatic Thresholds (watt × 10^{-16})				
Red	(655 $\mu\mu$)	164307.31	35229.61	626.99
Yellow	(580 $\mu\mu$)	496082.50	5969.26	27.96
Green	(522 $\mu\mu$)	61211.66	7651.46	1.953
Blue	(463 $\mu\mu$)	3759525.00	1051104.50	15.62
B. Chromatic Thresholds (watt × 10^{-12})				
Red	(655 $\mu\mu$)	12.63	3.52	.178
Yellow	(580 $\mu\mu$)	*	*	9.570
Green	(522 $\mu\mu$)	9.29†	1.17†	.143
Blue	(463 $\mu\mu$)	463.84	158.49	.812

* Yellow was called colorless even at full intensity.
† Green was always called blue, no matter how high the intensity.

CASE IV

John H., age sixteen. Secondary atrophy of the optic nerve following injury to the orbit by an automobile. Vision O D = 20/20 partly, O S = 20/70. This has since been reduced to 20/500 in the left eye. The ophthalmoscope shows a white nerve head with much contraction of arteries and veins. The form field is reduced to about 10° and green is visible 3° beyond the point of fixation (by clinical methods of study).

Clinical diagnosis: Progressive secondary optic atrophy (traumatic).

The energy values for the achromatic thresholds cannot be given—both eyes fatigued very rapidly, and as the first rough settings showed that the threshold values would fall well within the normal range, the more accurate determination was not undertaken. The chromatic thresholds values for the injured eye are given in Table XIV. Sensitivity to green and blue is normal; sensitivity to red is greatly reduced.

TABLE XIV

Total Amount of Light Entering the Eye (John H.)

Chromatic Thresholds (watt × 10^{-12})

Color		Left	Average (Normal)
Red	(655 $\mu\mu$)	1700.00	.178
Green	(522 $\mu\mu$)	.653	.143
Blue	(463 $\mu\mu$)	.106	.812

CASE V

John B. H., age twenty-three, student. Convergent unilateral squint since early childhood. Vision without glasses: O D = 20/500, O S = 20/300. Vision with glasses: O D = 4.50 S O .25 C ax 90 = 20/300, O S = 4.00 S O .50 C ax 90 = 20/12. Right eye shows convergent squint of 20°. Peripheral vision good; macular vision in the squinting eye amblyopic.

Diagnosis: Amblyopic ex anopsia as the result of the squint.

Amblyopia ex anopsia—defective vision attributed to lack of use—"may occur on account of obstruction to the rays of light falling upon the retina—*e.g.*, congenital corneal opacities, congenital cataract, and impervious persisting pupillary membrane; or in an eye which from early infancy has squinted, and has, therefore, not been concerned in the visual act." Parker (28) gives the following description of the process: "Because of defect in the fusion faculty, aided, perhaps, by hypermetropia (far-sightedness) and possibly from debility from disease, one eye shows an occasional transitory squint. This at first produces a diplopia (double images) from the fact that the two images do not fall on corresponding spots of the retinae. The eyes right themselves by muscular effort to parallelism to avoid this diplopia, but this power is soon lost, and the image of the squinting eye is suppressed, at first much as we would suppress the images falling on the left retina when we are looking through a microscope with the right eye; finally the squint becomes constant, diplopia no longer is noticed, and the retina of the squinting eye ceases to functionate. This condition is properly called *amblyopia ex anopsia.*"

As is shown in Table XV, both the light and color sense of the defective eye were found to be normal. This is what was expected by Dr. Peter, who believed it to be a matter of defective spatial perception.

TABLE XV

TOTAL AMOUNT OF LIGHT ENTERING THE EYE (John B. H.)

Achromatic Thresholds (watt × 10^{-16})

Color		Right	Average (Normal)
Red	(655 $\mu\mu$)	560.00	626.99
Yellow	(580 $\mu\mu$)	26.46	27.96
Green	(522 $\mu\mu$)	3.811	1.953
Blue	(463 $\mu\mu$)	16.48	15.62
		Chromatic Thresholds (watt × 10^{-12})	
Red	(655 $\mu\mu$)	.17	.178
Yellow	(580 $\mu\mu$)	4.68	9.570
Green	(522 $\mu\mu$)	1.219	.143
Blue	(463 $\mu\mu$)	2.102	.812

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